



Binding Perception and Decision Making

Distractor-Response Binding in Decision Making

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Abstract

The distractor-response binding effect (Frings & Rothermund, 2011; Frings, Rothermund, & Wentura, 2007; Rothermund, Wentura, & De Houwer, 2005) is based on the idea that irrelevant information will be integrated with the response to the relevant stimuli in an episodic memory trace. The immediate re-encounter of any aspect of this saved episode – be it relevant or irrelevant – can lead to retrieval of the whole episode. As a consequence, the previously executed and now retrieved response may influence the response to the current relevant stimulus. That is, the current response may either be facilitated or be impaired by the retrieved response, depending on whether it is compatible or incompatible to the currently demanded response.

Previous research on this kind of episodic retrieval focused on the influence on action control. I examined if distractor-response binding also plays a role in decision making in addition to action control. To this end I adapted the distractor-to-distractor priming paradigm (Frings et al., 2007) and conducted nine experiments in which participants had to decide as fast as possible which disease a fictional patient suffered from. To infer the correct diagnosis, two cues were presented; one did not give any hint for a disease (the irrelevant cue), whereas the other did (the relevant cue). Experiments 1a to 1c showed that the distractor-response binding effect is present in deterministic decision situations. Further, experiments 2a and 2b indicate that distractor-response binding also influences decisions under uncertainty. Finally, experiments 3a to 3d were conducted to test some constraints and underlying mechanisms of the distractor-response binding effect in decision making under uncertainty.

In sum, these nine experiments provide strong evidence that distractor-response binding influences decision making.

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1. Introduction

Is the patient suffering from Typhoid or Diphteria? Should I rent this flat or the other one? Should I go out with friends or re-read my favorite novel? Questions like these are omnipresent in our daily lives, meaning that we constantly need to make decisions, mostly under conditions of uncertainty. The types of decisions we have to perform are probably as numerous as the decision situations themselves. Sometimes, there is an objective criterion that can be used to evaluate the decision. For example, if we have to decide on the shortest route from our home town to a holiday destination, there always is an objective best solution, which requires the least kilometers of travel. If we want to find the best flat to buy, on the other hand, there is no objective basis, and our personal preferences play a role. Do I want the flat to live in it or as a financial investment? Would I prefer a roomy kitchen or a nice view?

Decisions are processes in which a person or a group – the so-called decision-maker – has to choose between different options (e. g., Jekel, 2011). These options could be e. g., objects, statements, actions or long-term strategies. Possible options between which we have to choose could be wedding partners, a leisure activity for the evening, or our next career step. In order to make a decision, the decision-maker has to take information about the problem into account. In case of the search for the shortest route to a vacation place, the decision-maker could try to find out the distance between several waypoints on the map and use this information to calculate the actual distance for several options. In this case a rational strategy to combine the available information would be to add the

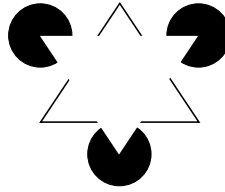


Fig. 1.1. The Kanizsa triangle as an example for inference processes in visual perception.

distances between all waypoints on a route to actually infer the criterion value on which the decision is based. In some cases the actual optimal option might even be accessible directly, for example, by simply looking up the shortest route in a route planner. In other cases, it may be less clear how to combine the available information. A judge or a jury in a criminal court, for example, are usually presented with a large body of evidence from which they have to infer whether the accused is guilty or not. In some cases, the environment may present or even force information on us, which is irrelevant to the actual decision. In case you plan to buy a house, for example, the current owner may go to great lengths to point out the benefits of the currently installed kitchen, which may be completely irrelevant if you just plan to install your own kitchen anyway.

All these decisions have in common that we are consciously deciding between options, whether these options are different routes, different flats, etc. Usually, we are aware that we are deciding at that moment between different options, and even if we let our intuition guide us, so that we are not aware of the actual process, at least we know that we somehow decided. However, often we also decide subconsciously, without even the awareness that we decided at all. Is there a glass door in front of the building or not? Is this object closer or another one? While these questions do not look like decisions at first, they do carry some important aspects of decisions. To decide if one object is in front of another one, one first has to determine if one object occludes the other – at least if the disparity from the eyes does not give an indication of the spatial relationship. However, to determine if one object occludes the other, one first has to reason if what we perceive is the complete object, or if we only perceive a part of it. So, we have to reason

about meaningful completions of the objects we see. For example, in the illusion shown in Figure 1.1, one first has to assume that the three objects shown are complete and not incomplete circles. Only under this assumption one can infer that there must be a triangle in front of the three circles which we just do not see because it has the same color as the background. This process has in common with the examples for decision problems presented above that we need to infer something that we do not see or perceive otherwise based on information which we know or perceive. However, it also differs in the sense that it is automatic and not conscious. We do not even know that we are deciding whether there might be a triangle or not, we just do the inference and adapt our perception, for instance by seeing the area of the triangle as somewhat more white than the rest.

Still this example shows that basic perception already contains some characteristics of decision making. One possibility of course is that these common characteristics are due to pure chance. Perception and decision making simply both require inferences and so we have multiple ways for making these inferences. A different hypothesis one could assume is that actually the brain only has a single way for doing inferences. Decisions as part of the perceptual processes may be done by the same neural structure that also handles decisions of which we are aware. Now which of these two hypotheses is correct?

1.1. Goals of this Thesis

The main goal of this thesis is to produce further evidence regarding the research question whether inferences in perception are done in the same way as conscious decisions. One way to test this hypothesis is by testing if the same effects that have been studied for perception can also be reproduced for decision making. Since there are too many known effects for perception, I will focus on a single effect, which is then extensively tested in three sets of experiments. Should this effect also exist in decision making, this would strongly indicate that decision making and perception are not performed using different

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mechanisms, but rather that the same mechanisms, which were evolved for perception are now re-used as part of our higher cognitive functions.

The general idea that perception and decision making are based on similar principles is not entirely new in the scientific literature (e.g., Glöckner, 2010; Nakayama, He, & Shimojo, 1995, 1990; Rock, 1983). Rather, perception is often seen as a process of inference (Nakayama et al., 1995, 1990; Rock, 1983). However, it is often not clear, if this is a specialized inference process, possibly driven by simple algorithms which can solve the problems of day-to-day perception (e.g., Nakayama et al., 1995), or if this process can also generalize, and be adapted to a large number of situations, just like the mechanisms which solve decision problems of which we are aware. On the other hand, there is some evidence that models which first were developed to explain Gestalt processes, can also be adapted for decision making (Glöckner, 2010). The perceptual figures like the Kanizsa triangle are often explained using Gestalt processes, so if models of these processes are able to emulate decisions, this is a strong indication that the same structures which allow us to perceive our environment, are also the same structures enabling us to decide.

Even though there already is some evidence that decision making and perception are based on the same processes (Glöckner, 2010; Nakayama et al., 1995, 1990; Rock, 1983), research is carried out mostly along separated lines (Bröder & Schiffer, 2006). If the hypothesis of common processes should be correct, this would also imply that all theoretical concepts found for perception also apply to decision making and vice versa. This offers a great opportunity to re-use a vast amount of existing research in each of the fields as part of the other. Hence, another goal of this thesis is to present some evidence that theoretical concepts re-used from the field of perception can predict effects in the field of decision making. Furthermore, the goal to show the existence of a common theoretical basis, also indicates, what kind of effects should be studied at first in such an undertaking. The goal should be to test theoretical concepts, for which no or only little previous indication in the research on decision making exists. For example, research on decision

making is often based on single trial effects. There are many theories that predict the behavior to be the same in each trial. For example, the *desired level of confidence* (DLC, see Hausmann & Läge, 2008) assumes that information search is stopped after a certain level of confidence for one of the options is acquired. The confidence in this case is based solely on cues presented during the current trial. Research on perception, however, is often done based on intertrial effects, i. e., effects in which the immediately preceding trial influences the current trial (e. g., Fox, 1995; Frings et al., 2007; Hommel, 1998; Rothermund et al., 2005). For example, the information presented in the previous trial may lead to faster or slower perception and/or response production, based on its relation to the information presented in the current trial. There is only little research on intertrial effects in decision making (for an exception see e. g., Kusev, van Schaik, & Aldrovandi, 2012).

Also, to point to a common structure of decision making and perception, it is necessary to review theories from both fields, in order to find possible existing convergence points. Which concepts are shared among both fields of research? What theories are used to explain these concepts in each field? What effects are predicted by these theories in each field?

Taken together, these considerations provide a detailed picture of what kind of effect should be studied in the area of decision making to point to a link between decision making and perception. The effect should have a solid theoretical foundation in the field of perception and the effect should have a theoretical relation to a concept, which is shared by both fields. One effect which fulfills these criteria, is the distractor-response binding effect. In the following section this effect will be briefly illustrated. A full theoretical explanation of this effect will be presented in Section 2.3.

1.2. Distractor Response Binding in Perception and Decisions

In everyday life, we frequently have to distinguish relevant from irrelevant information. Even though irrelevant information is often ignored on the conscious level, it can influence actions (e.g., Frings et al., 2007). For example, imagine you are lying on a beautiful meadow with your fiancée. Her favorite colors are red and white, but she much dislikes yellow and pink. On your right side you discover a red flower surrounded by yellow ones. Suddenly you have the idea to collect a bouquet of flowers for her. To grasp the red flower, you have to ignore the yellow flowers. Immediately, after you plucked the red flower, you notice a white flower, which again is surrounded by yellow flowers. To collect the bunch of flowers, you also grasp the white one. This time your action will be a little faster and smoother than the last time. The reason is that you automatically saved the action “grasping”, the relevant stimulus “red flower”, and even the irrelevant stimuli “yellow flowers” together in memory for a short time. Now when you see the yellow flowers, these will help you retrieve the appropriate action, so that you can execute it more easily. The association may even lead you to accidentally pick a flower, which your fiancée does not like. If you saw a pink flower surrounded by yellow ones instead, the yellow flowers alone may lead you to execute a grasping action, although normally you know that your fiancée does not like pink flowers. In general, executing or even just planning an action creates a link between the action and any kind of stimulus present while the action is planned or executed, no matter if this stimuli is relevant or irrelevant for our action (however, see Section 2.3.2 for some limitations). If you encounter any of these stimuli again – even the irrelevant ones – and you want to perform the same action, your action will be facilitated. But if you want to make a different action, your action will be hampered, or in some cases you may even execute an incorrect action.

This example shows how previous actions influence subsequent behavior. The surroundings of the red flower leads to a better performance if another flower has to be picked in a similar surrounding. If perception and decision are based on the same processes, it

should be possible to think of a similar example in the field of decision making. Imagine you recently moved to another city. To celebrate moving into your new place, you are looking for a bar which offers great beer. You stop by a bar from which you hear loud metal music and which prominently displays a sign with a logo of an unusual beer brand. Your experience tells you that bars which sell an unusual beer also carry a large selection of beers in general. You do not think that there is any connection between the music and the choice of beer, after all you have been to metal bars with good and bad beer selection before. So you ignore the music, and decide to enter the bar based on your experience about the unusual beer brand. However, as soon as you want to order, you notice that it time has passed faster than you thought, so you go home instead. On the next day, you would like to make up for the celebration you missed, however, as you are in a different part of the city, you have to search for another bar with great beer. Again you find a bar, from which you hear loud metal music. This time, however, the bar only carries an ordinary “Bitburger” sign. So tonight there is no cue that indicates that this bar might have a good beer selection. However, both bars have in common, that they play loud metal music. Yesterday you believed that this is not a valid indicator of the beer selection. Still, the same style of music was played at a bar, which you believe might have had a good beer selection. Will you enter the bar because of this (probably irrelevant) accordance in music between both bars? After all, you never linked the music style to the beer selection, and yesterday you had no chance to find out if there might be a link.

Probably you will answer this (rhetorical) question with “no” because as a rational decision-maker, you know that you should only consider relevant bits of information for your decision and ignore irrelevant ones. Nevertheless, there are some situations in which researchers could show that people considered irrelevant information (e. g., Huber, Payne, & Puto, 1982; Nisbett, Zukier, & Lemley, 1981; Platzner & Bröder, 2012). Furthermore, if decisions and perception share a common structure, the same effects of distractor-response binding should apply here. During the previous night, when you encountered the bar and

you decided to enter, the complete event was stored, including the irrelevant metal music, together with the decision to enter the bar. So this encounter of the event has created a link between metal music, a good beer selection, and entering the bar. This then can lead you to enter the bar on the next day, although there is no actual cue which indicates that this bar offers what you search for. One might be tempted to explain such a behavior by learning. However, learning in the classical sense requires some kind of feedback. On the previous night, you only *decided* that there might be a good beer selection, but you did not *find out* if this assumption is true. Hence, no feedback was given which may have led to learning a connection between metal music and a good beer selection.

1.3. Outline of this Thesis

To answer the research question of whether distractor-response binding plays a role in decision making on a theoretical basis, I will start by reviewing theories of perception and action which may be integrated into theories of decision making. Therefore, I will present the underlying mechanisms of object perception and action control in Chapter 2. One main focus will be put on the theory of event coding, which provides an account for the effects studied in this thesis (Section 2.3). In Chapter 3, I will demonstrate that irrelevant information can influence decision making. In the following Chapter 4, I will highlight common theoretical foundations and possible theoretical links between the fields of decision making and perception/action control. In Chapter 5, I will present the hypotheses underlying this thesis. After the theoretical introduction, I will present empirical findings to support my hypotheses. In the first set of experiments described in Chapter 6, I show that distractor-response binding plays a role in deterministic decision making. Further, I can present evidence demonstrating that distractor-response binding also influences decision making under uncertainty (Chapter 7). In the last set of experiments, I test possible constraints and underlying processes of distractor-response binding in decision making under uncertainty (Chapter 8). In the final part of my thesis,

I will discuss the empirical findings (Chapter 9) and present conclusions and perspectives for future research (Chapter 10).

Part I.

Theory

2. The role of Distractors in Action Control

Usually, our environment presents a vast amount of information to our senses. At any given moment, we are surrounded by a multitude of objects, which can be perceived simultaneously. For example, our ears can pick up ambient sounds from a nearby street and our stomach may signal that we are hungry or full, depending on the time of our last meal. However, most of the time we do not tend to notice most of this information, at least not consciously. While at first glance, this may seem as a shortcoming of our cognitive system, this constant filtering is actually a necessary precondition for enabling us to interact with the environment in a meaningful way (Allport, 1987). The reason is that at any time only some parts of the environment are needed to inform our actions, while others may carry different – in some cases even conflicting – information. For instance, if we see a green light at an intersection we want to cross, we have to decide whether this green light is meant for us or for the drivers who want to do a turn. In case the green light is meant for cars doing a turn and the light meant for us is red, we better do not consider the green light when we decide whether to cross or to stop, lest we might cause an accident. This example shows that it is in many cases necessary to select stimuli to consider and which better not to consider¹. Hence, when we act, we

¹In the case above the green light for turning traffic should not be included when choosing the appropriate action. However, this does not indicate that the stimulus is not processed at all. For example, it may be possible that the person who perceives the green light may later have to remember the color, for example when testifying in a trial because of an accident. Nevertheless, the stimulus is task-irrelevant at the moment when the car is approaching the intersection

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have to focus on specific parts of the environment with which we are interacting. During focusing, we have to inhibit parts of our surroundings or even parts of a focused object to act adequately. For example, when you are talking to a friend on the bus, you have to concentrate on his voice and ignore all other voices and sounds. This is a quite common task in day-to-day life and we are able to single out a particular speaker even if another person is much closer to us or talks much louder. This phenomenon is called the *cocktail party phenomenon* (Cherry, 1953). However, even irrelevant stimuli are processed in our mind. So, if a different person on the bus said your name in her talk, your attention might be drawn away from your friend towards the other person (Moray, 1959). This phenomenon shows that ignored stimuli are processed unconsciously, but as soon as they become relevant they can be drawn to conscious processing.

As ignored stimuli can be unconsciously processed, in some cases they cannot be fully inhibited and may influence the actual task to be performed (e. g., Moray, 1959; J. R. Simon & Wolf, 1963; Stroop, 1935). The experimental paradigm of this thesis, i. e., the *distractor-to-distractor priming paradigm* (Frings et al., 2007), builds on the fact that task-irrelevant information is nevertheless processed. In this paradigm, first a prime display including task-relevant information (*target*) as well as task irrelevant information (*distractor*) is presented. For example, in the task shown in Figure 2.1, participants have to respond to the middle letter (*target*) and ignore the flanking letters (*distractors*). In the prime displays shown in Figure 2.1 the letter “D” is relevant whereas “Z” is irrelevant (i. e., not correlated with the response nor with the relevant letter). Then in the subsequent probe display the same (distractor repetition trials, DR, Figures 2.1a & 2.1b) or different irrelevant stimuli (distractor change trials, DC, Figures 2.1c & 2.1d) are presented. Simultaneously, the response indicated by the task-relevant information (shown as the hand position in Figure 2.1) is varied orthogonally, leading to response repetition (RR) trials or response change (RC) trials (Frings et al., 2007, see Figure 2.1). Experiments show that participants respond faster if the response relation and distractor

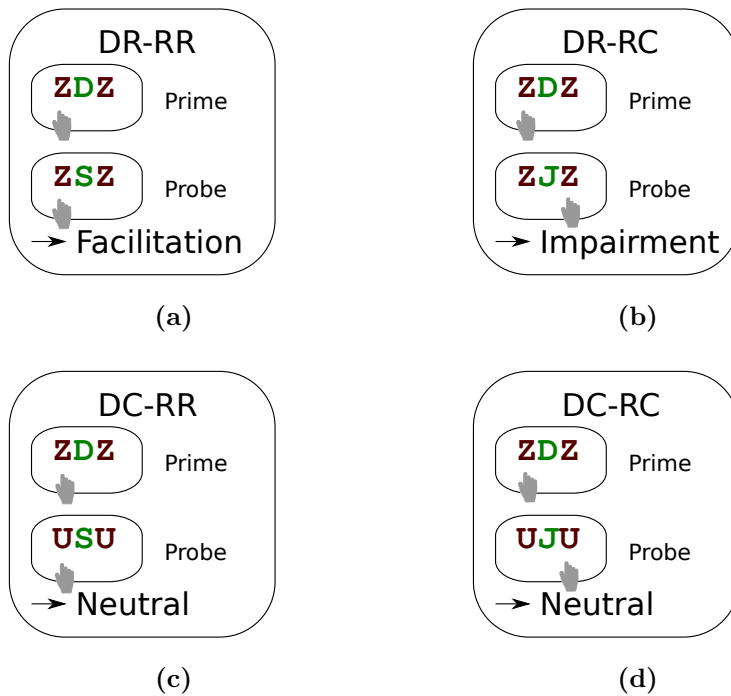


Fig. 2.1. An example for the distractor-response binding effect in a flanker task. Participants have to respond to the green letters and ignore the red flankers. “D” and “S” require left hand responses and “J” and “K” right hand responses. If the distractor remains unchanged between the displays (a & b), participants respond faster if the required response also has to be repeated (a), but respond slower if the required response has to be changed (b).

relation are the same (DR-RR and DC-RC trials), while they respond slower if the response relation and distractor relation are different (DC-RR and DR-RC trials) (e. g., Frings & Rothermund, 2011; Frings et al., 2007). Again this indicates that the irrelevant information is not fully inhibited but somehow processed. Furthermore, this results from this experimental paradigm also imply that the processed information is not only used for the current task, but also stored in memory (Hommel, Müsseler, Aschersleben, & Prinz, 2001), so that it can influence tasks that follow shortly afterwards.

2.1. Object Perception

In order to understand how ignored information² is integrated and processed, it is necessary to consider how we normally perceive relevant information. Focusing our view even further, I will now consider theories on how the basic perceptual information, e. g., sensory output from the receptors on our retina, is grouped and segmented to allow the coherent perception of objects in our environment. I will focus on the basic principles of object perception in the visual domain, however, similar principles seem to apply when considering other sensory domains or even the integration of multiple sensory domains (Styles, 2005).

There are many problems to consider in the area of object perception. The first problem is how basic stimuli on the retinal surface are interpreted, for example to recognize different objects. Our environment is full of different objects which are all just represented by activations of rods and cones on our retinal surface. How are we able to tell which

²“ignored” in this case means that something is not processed consciously, e. g., because it is not relevant for the current task. This does not imply that it is not processed subconsciously. For the cocktail-party phenomena, for example the voices of other speakers are ignored, i. e., not processed consciously. However, as soon as your name is spoken, they may become the focus of attention. Moreover, recognizing one’s own name requires subconscious processing. This shows that even ignored information is processed (Moray, 1959).

activations belong to which object? This problem is even graver if we consider that the same object may represent itself in a large number of different angles, often also in different configurations or poses. For example, animals can be standing, lying, crouching, etc. All these different angles and configurations present themselves as patterns on the retinal surface, which have almost nothing in common. The second problem is how to perceive an identity or continuity of the same object across time or space. Often objects consist of different parts making up a whole. How do we know that these parts belong to the same object and not to another one? Also, often objects may change over time. Treisman (1988) presents a striking example of how much an object can change, while still being perceived as the same object. “A distant aeroplane retains its continuity as a single perceptual object, even when we see it flap its wings and alight on a nearby tree, thus forcing us to change the label we initially assigned. A new node, for bird instead of aeroplane, becomes active, but we see a single, continuing object.” (Treisman, 1988, p. 219) Another example is the phi phenomenon (Wertheimer, 1912), a special case of apparent motion, in which two successive images of a stimulus set off at a distance induce a perceived motion. How is it possible that we perceive these two stimuli as the same object, and interpolate the apparent motion between the stimulus positions, although this information is not presented to our visual system? One further problem that is often considered in object perception is how we are able to perceive an object as belonging to a larger category of objects. For example, how do we know that the object in front of us is a table, although tables can take a variety of shapes, rectangular, round, with almost an arbitrary number of legs, different heights, different colors, etc. Even if the table is taken apart into pieces, in many cases we will likely still be able to recognize these pieces as parts of a table.

One of the first theories of object perception was put forth by the *Gestaltists* (e. g., Koffka, 1935). The main question considered by the Gestaltists was the problem of *figure-ground segregation*. This question addresses how we are able to perceive some

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stimuli as a figure or object against a background. Closely related to the question of figure-ground segregation is the question of perceptual grouping, i. e., how are different stimuli, possibly from different locations, combined to form a perceived object? The Gestaltists proposed a number of *Gestalt laws* that govern under which conditions two stimuli are perceived to belong to the same object (e. g., Köhler, 1929; Metzger, 1966). For example, under the *principle of similarity* stimuli resembling each other, e. g., in terms of color or shape, are taken to belong to the same object. The basic underlying principle for all these Gestalt laws is the *law of Prägnanz*: “Of several geometrically possible organizations that one will actually occur which possesses the best, simplest and most stable shape” (Koffka, 1935, p. 138). Although this principle was at first only considered for geometric shapes, it can also be generalized to other types of perceptual features. For example, it is simpler to group multiple stimuli co-occurring at the same position, e. g., color and geometric shape than to group a color occurring at one position to a shape occurring at a different location. Most of the Gestalt laws are still used today and form the basis for grouping principles in other theories (Frings & Rothermund, 2011).

While the Gestaltists proposed many principles governing which stimuli are grouped to form a figure, these principles neither consider the underlying mechanisms of grouping, nor the question of how these stimuli are perceived in the first place. In order to understand how the stimuli are perceived it will be necessary to consider the biological basis of object perception. The first components of our visual system are only able to recognize very simple features. Cones and rods in our retina respond to rays of light coming through the lens into our eye, similar to a camera. The activations of the rods and cones are sent to the primary visual cortex (*area striata*, V1), which performs various types of edge and grating detection (Hubel & Wiesel, 1959). The primary visual cortex then sends this information via different pathways to other parts of the brain. One of these pathways is the *ventral stream*, which projects to the *inferotemporal cortex*. The other pathway is called the *dorsal pathway* which projects to the *posterior parietal lobule* (Milner & Goodale, 1995;

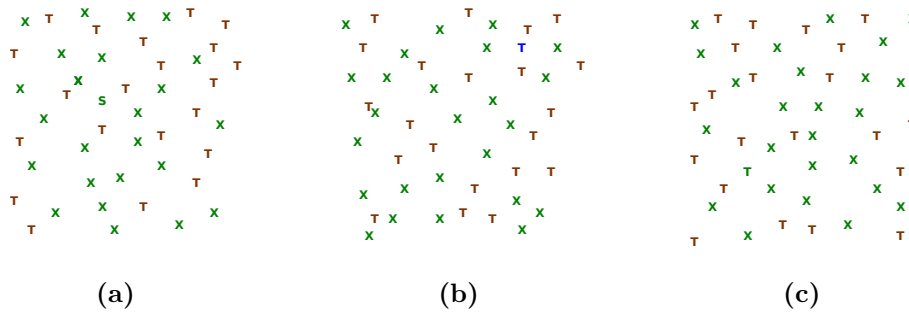


Fig. 2.2. Examples of displays for one of the experiments in Treisman and Gelade (1980). The green “S” (a) and the blue “T” (b) are easily detectable, whereas detection of the green “T” (c) requires checking all letters serially.

Mishkin, Ungerleider, & Macko, 1983). The ventral stream is mostly concerned with information required for the recognition of the object type. For example, color and shape information is transmitted through this pathway. The dorsal pathway, on the other hand, is thought to be responsible for transmitting spatial information and information required for visuomotor performance (e. g., Müsseler, 2002). Information transmitted via this channel includes e. g., perceived motion or information about stimulus location (Milner & Goodale, 1995; Mishkin et al., 1983). In other terms, the dorsal stream is responsible for the “where” information and the ventral stream for the “what” information (Styles, 2005; Treisman, 1996; but cf. Müsseler, 2002).

As this account shows, information about the same object is distributed among several different areas of the brain. If we see a moving red dot, we perceive both the movement and the redness as belonging to the same object. However, both movement and color are features of the object which are encoded as feature codes in different areas of the brain. How are these feature codes combined to form a coherent perception of a moving red dot? In addition, Treisman and Gelade (1980) present evidence that even features encoded via the dorsal stream are processed by different cognitive modules, which again have to be combined for coherent perception. In one of their experiments participants had to

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decide if a special kind of target stimulus³ was present among other distractor stimuli or not (Visual search paradigm, see Wolfe, 1998). In a first condition participants had to pick out a single green or brown letter “S” from a background of distractors consisting of green letters “X” and brown letters “T” or a single blue letter “X” or letter “T” from the same background (see Figure 2.2). In the second condition the participants had to find a single green “T” among the same background. The number of distractors presented was varied as an independent variable. Treisman and Gelade (1980) argue that one might expect performance to be worse in the first condition, as there are four possibilities for the shape and color combination of the target in this condition (green “S”, brown “S”, blue “X”, blue “T”) whereas in the second condition participants only had to consider a single possible target. However, in the first condition participants responded within about 400ms regardless of the number of distractor letters. In the second condition, however, response times increased linearly with the number of distractor letters. Treisman and Gelade (1980) take this to indicate that shape and color are represented within different parts of the brain, i. e., different cognitive modules. In these modules the perceived features are encoded as feature codes, which are the neural firing patterns representing the perception of the feature within the corresponding module. For example, perception of a red object is encoded using the “red-code”. Each module is only responsible for a single feature dimension, i. e., a set of features from the same semantic category. For instance, the color module is responsible for representation of all color codes. In case the target can be selected by a single module, recognition will be instantaneous; however, if both the shape and the color module are required, a serial scan is needed to determine which letters have a special feature on both modules. If we take this as evidence for processing of different features in different parts of the brain, the question remains, how we perceive an object to have a shape and a color at the same time. Furthermore, it is

³In this experiment target refers to the object that has to be detected. Distractors are all objects which are not targets.

necessary to assign the features encoded in different modules in a coherent way. If we are presented with a green “X” and a brown “T”, we have to assign each color to the correct shape so that we do not perceive a green “T” and a brown “X”. In general the question how conjunctions of multiple feature codes are constructed is called the *binding problem*. Via binding, different features or stimuli are thought to be combined into a coherent representation. According to Treisman (1996), there are at least seven different types or subproblems of the binding problem:

Property Binding in which different properties, e. g., color and motion have to be bound to the object possessing these properties.

Part Binding in which parts of an object must both be combined into the object they belong to and at the same time be segregated from the background.

Range Binding in which a single property signaled by different populations of receptors or neurons has to be combined into a single representation. One example would be the perception of the color purple, which has to be combined from signals of receptors for blue and red becoming activated simultaneously.

Hierarchical Binding in which spatial boundaries of objects are bound to the properties that carry them. For example, a boundary could consist of a change in color, in which case the boundary has to be bound to the color stimulus. That means, it is necessary to represent that the spatial boundary was caused by a color change and not, for example, by a texture change.

Conditional Binding in which one property is required to allow for interpretation of another property. For example, if some object occludes another, it is possible to infer that the occluding object is in front of the occluded object.

Temporal Binding in which different states of the same object over time are integrated as belonging to the same object.

Location Binding in which the location of an object has to be bound to the object itself.

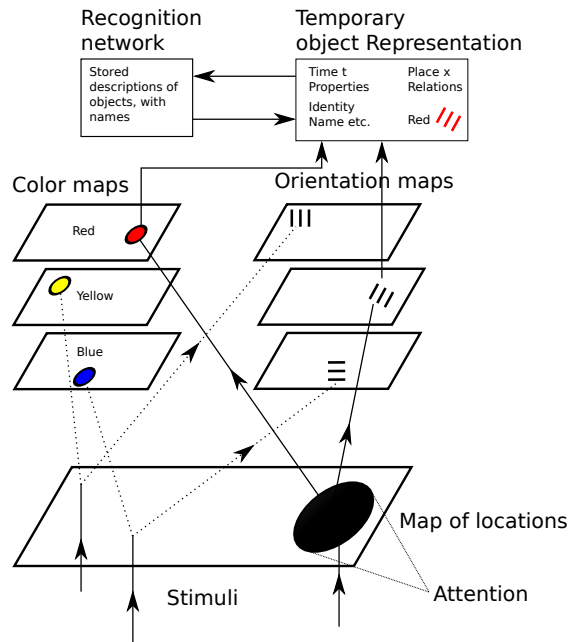


Fig. 2.3. General framework for perceptual processing according to Treisman (1988, p. 202)

The problem of *location binding* arises because “what” and “where” information is distributed along different pathways. The problems of *part binding* and *temporal binding* reflect the basic questions on how we achieve spatial and temporal continuity that were presented at the beginning of this section. At this point, these questions can be seen as parts of a larger question, i. e., how different stimuli and features are integrated in general.

Treisman and Gelade (1980, see also Treisman, 1988, 1996) present a theory of feature integration as a solution to the binding problem, the *feature integration theory* (FIT). The basis for this theory is presented in Figure 2.3. According to this theory, all features are first combinedly represented in a *master location map*. This master location map contains information about the presence and location of all features that are perceived. However, it does not contain any information about which feature is present at a given location. After representing the features in the master location map, they are then forwarded to special modules, each of which is responsible for a single feature dimension, e. g., color or

orientation. Within these modules, each feature of a dimension is separately encoded on a *feature map*, where the location of that particular feature is indicated. For example, when seeing a round red dot in the upper left corner of the visual field, this perception would first lead to an entry in the upper left corner of the master location map. Then this perception would be further processed by the color and the shape module. In the color module, an entry would be created in the red-map in the upper left corner, and in the shape map an entry would be created in the round-map at the same position. In order to perceive a coherent red dot, the information in all these maps has to be bound. However, the feature modules are not able to combine the information by themselves. To bind different features from different modules to each other, the common index in the master location map is required for reference. The master location map can be scanned for objects, by focusing attention on a contiguous spatial area (spotlight mechanism, see Posner, Snyder, & Davidson, 1980). Only features, which are referenced in the part of the master location map currently under the spotlight, can be bound reliably and correctly. This does not mean that other features will not be bound at all. However, for features which are not under the spotlight, there may be conjunction errors, i. e., a feature from one object may be bound to a different object (Treisman & Gelade, 1980). Once different features have been bound to an object, this object is represented in short-term memory and can be compared to known object templates from long-term memory. The previously learned object representations can also be used for top-down control of the binding process, to avoid conjunction errors (Treisman, 1988). When looking for a given target among different distractors like in Figure 2.2, there are several possibilities in this theory. If the target differs from the distractors along a single dimension, and the distractors themselves do not vary much along the same dimension, the module for that dimension can be used directly. In this module the special feature is detected immediately in the corresponding feature map. Then, using the location in the feature map, attention can be directed to the location in the master location map which starts the binding process for

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that object. However, if the target differs from the distractors in a combination of features coming from different feature dimensions, no single module can be used to detect the target. Instead it is required to bind each object in turn by scanning them in the master location map, which leads to search times linear in the number of distractors (Treisman, 1988; Treisman & Gelade, 1980). Treisman (1988) also tests some examples of *illusory conjunctions*. For example, when participants have to recognize two digits, one on each side of three colored letters, attention will only be directed at the digits. In this case, if participants are asked about the color of the letters, they will name the correct letters and the correct colors, but the assignment of colors to letters may be wrong. These binding errors can be influenced by using previous knowledge as a form of top-down control. For example, if the participants are shown shapes and told that these shapes represent lakes (ellipses), logs (bars), carrots (triangles) and trees (arrows), participants are more likely to perceive the color that is usually expected for the presented object (Treisman, 1988). This top-down control both influences perception if the object is presented in the expected color, as well as when it is presented in a different color. Thus it can both rectify incorrect binding, e. g., if a lake is presented in blue, but also create new incorrect binding, in case the presentation does not correspond to reality, e. g., if a lake is presented in orange (Treisman, 1988). This correction process does not seem to use the features presented in the feature modules, but instead just replaces these features in the short-term representation of the object. For example, participants are not more likely to perceive a blue lake upon presentation of an orange ellipse when there is another blue object present, than when there is no other blue object, from which this corrected feature could be taken. Hence, the top-down control does not so much change bindings between perceived features, but rather replaces features with those taken from memory, which are immediately bound to the corresponding objects (Treisman, 1988).

This theory so far explains how property binding of features presented at the same time can be achieved. However, this still leaves the question unanswered, how we can

perceive the change of the object state over time, i. e., how temporal binding is achieved. For this Treisman (1988) proposes the mechanism of *object files*. Object files are the episodic representation of the states of attended objects. Treisman (1988) compares these object files to police files, in which all information about a crime is recorded over time. If new information is acquired, this information can be appended to the existing object file. Object files do not only serve as a solution to the problem of temporal binding, but can also serve other functions in human perception. Treisman (2006) names six other possible uses of object files. First, object files are the actual parts into which a scene is parsed. This makes it much easier to attend a whole object, than to single out its features. Second, object files can also be used to serve as a representation of an object we have never encountered before if the bound features cannot be matched to any object template in long-term memory. Third, object files can be used to represent multiple instances of the same object type. If all we could vary was the activation of the type node, this would make it impossible to represent a prototypical instance of a category differently from multiple instances of that object type. Fourth, object files are the loci to which features are bound. The feature integration theory proposes that multiple features are bound by using location cues. These features are bound within objects files. Fifth, object files serve as episodic representations of changes of the object over time. And finally, object files serve as an interface between early visual processing and top-down control from memories. Object files provide the information, which is combinedly compared to templates of existing object templates in memory. There is a large body of empirical evidence that indicates the existence of object files (Treisman, 1988, 1996; Treisman & Gelade, 1980; Treisman & Kahneman, 1983). Moreover, the *negative priming effect* (Allport, Tipper, & Chmiel, 1985) is often interpreted as evidence for the existence of object files (e. g., Hommel et al., 2001) or other types of episodic retrieval (e. g., Neill, Valdes, Terry, & Gorfein, 1992). However, this effect has also been interpreted as evidence for inhibitory processes of selective attention (Houghton & Tipper, 1994), making the evidence less

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clear. Nevertheless, there are other empirical findings, which point to the existence of object files. For example, Treisman and Kahneman (1983) report an experiment in which participants were presented with four black squares. In all of these squares, a vertical or horizontal line was presented for a brief moment. Then these objects moved to a different location, and after the movement, another horizontal or vertical line was presented in all of the squares (negative trials). In half of the trials during the second presentation one of the lines was instead replaced with a plus in one of the squares (positive trials). Participants had to tell whether there had been a plus in any of the squares or not. Participants were considerably slower in negative trials if the lines were differed in orientation before and after the movement, than if the lines had the same orientation at both times. In case the lines were presented horizontally before the movement and vertically afterwards, the two lines together formed a plus, however they were not presented simultaneously nor at the same position. Treisman and Kahneman (1983) interpret this effect by stating that both the first line as well as the second line are represented as features in the object files for each of the squares. Hence, in the case of a negative trial where only a horizontal line was shown both before the movement as well as afterwards the object files for all squares only contain the feature “horizontal line”. On the other hand, in positive trials, i. e., trials in which a plus was shown, the object file for the one square in which a plus was shown, contains the features “horizontal line” and “vertical line”, which together represent the plus. By looking for any object file containing these two features, the cognitive system can easily detect if there had been a plus sign. However, in negative trials, in which there first was a horizontal line in each of the squares and then a vertical line, each of the object files would contain the feature “horizontal line” (from before the movement) and “vertical line” (from after the movement). Hence it is not enough to simply scan for object files which contain these two features, it is also necessary to test whether both features were present simultaneously or in sequence. This requires additional checks on the object files, which lead to worse performance in these cases. By moving the squares to different

position, Treisman and Kahneman (1983) could also show that the knowledge about the states and features of the object is moved if the object moves, and simultaneously exclude other possible explanations such as e. g., retinal afterimages, which may have combined horizontal and vertical lines.

While there is much empirical evidence for this theory (Treisman, 1988, 1996; Treisman & Gelade, 1980; Treisman & Kahneman, 1983), there is also some criticism. For example, Houghton and Tipper (1994) point out that it is unclear how it is possible to shift attention deliberately from object to object if attention itself is a precondition for the perception of an object. Also, considering the biological basis presented here so far, it is known that “what” and “where” information is processed through different streams, so how is it possible, for example, to build up a red-map, containing the locations of all red objects? This would require information from both streams simultaneously, which means binding would already be required to build up the feature maps. Furthermore, according to Treisman and Gelade (1980), the features to be bound are rather low-level, e. g., colors, basic shapes, orientations etc. If the object file is made up of such low level features, how does object recognition work? A simple template mechanism that matches the current object file against a set of previously encountered objects would require a large number of templates to account for the variability among different instances from the same object category. And finally, it has been pointed out regularly that attention does not only seem to serve the purpose of allowing coherent object recognition, but rather as a general mechanism to allow for coherent action (e. g., Houghton & Tipper, 1994). However, as the feature integration theory is only concerned with object perception, there is no consideration on how object perception and action work together. At least some of this criticism will be addressed by the theory of event coding (see Section 2.3), which builds on the feature integration theory among others.

The theory presented so far still leaves the question how object binding and the construction of object files are achieved, i. e., which mechanism is used to implement

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the theory presented above. Treisman (1996) names several mechanisms, which can be used for binding: grandmother cells, which respond only to feature conjunctions uniquely defining an object (e. g., Gross, 2002); local cell assemblies onto which the pathways from multiple feature maps converge; a serial scan mechanism that scans the visual field and conjoins those features, which are scanned simultaneously; detection of temporal contiguity; synchronized firing of cells representing features of the same object⁴. It is likely that the cognitive system does not rely on only one of these mechanisms, but that many of these mechanisms are combined to perform the necessary functions for object recognition (Treisman, 1996).

The two mechanisms that have been discussed the most in recent literature are convergence and synchronization/correlation (Moeller, 2011). *Convergence* means that lower-level features are repeatedly grouped into more complex higher-level features. For example, at one level the features may consist of dots and lines, while at the next level a set of two dots above a vertical line and a horizontal line are recognized as a face⁵. The basic principle is that many lower level features are bound into fewer higher level features. At the lower level the cells respond to less specific stimuli, while they become more specific with each subsequent level (Barlow, 1972). This principle has given rise to the idea that at a sufficiently high level, the neurons only respond to very specific stimuli, e. g., one specific person (so called *grandmother cells*, see Gross, 2002). While there may be some cells representing very complex stimuli we encounter frequently (Quiroga, Reddy,

⁴The list of binding mechanisms given by Treisman (1996) contains both behavioral and cognitive mechanisms as well as neuronal mechanisms. I will focus on the neuronal mechanisms here, as these most likely can be shared by structures which perform decision making and perception.

⁵This example is oversimplified, however, it can serve to give a basic notion of how convergence works. In the actual visual cortex faces are most likely build up from much more complex higher level features. One reason for this is that such a simple recognition of a face as two dots and a line would fail if one eye is missing, or if the mouth is occluded. We can easily recognize faces with missing or covered eyes or other occluded parts, though.

Kreiman, Koch, & Fried, 2005), it seems unlikely that every stimulus converges to a grandmother cell. The required number of cells would simply be too large if we needed a single cell to represent all our family members, friends, co-workers, or even the person we just met five minutes ago at a bar. Hence, the principle of convergence can explain some parts of our ability to recognize persons or objects, but not all of it.

The principle of *correlation*, on the other hand, assumes that an object is recognized by *synchronizing* the firing pattern of multiple cortical areas each of which represents a different feature of the object to be recognized (Engel & Singer, 2001). For example, in monkeys, visual information is spread out to as many as at least 30 different cortical areas. If a complex stimulus is encountered, multiple of these areas will become activated, indicating certain features of the object to be recognized. These distributed single feature representations are bound by synchronizing these areas in the *gamma range* (30 – 80Hz). However, this synchronization only occurs if the features represented by the activation in each area belong to the same perceived object. It is assumed that the synchronous response of these neurons serves as some kind of tag on these responses indicating that they belong to the same object. The synchronous activation also separates these responses from asynchronous responses to other features. Furthermore, the synchronous activity of multiple brain areas also produces distinct spikes that can easily be picked up by other areas of the brain (Engel & Singer, 2001). Nevertheless, synchronizing of multiple brain areas whenever a set of co-occurring stimuli appears is an expensive operation in terms of the time required to perform the binding.

Whereas the previously presented theories emphasize the computational complexity and the interaction of top-down and bottom-up processes in attention, the *ecological theory* uses the idea of purely bottom-up direct perception (Gibson, 1979; Styles, 2005). The ecological theory, assumes that there is no necessity for a computationally complex approach to object recognition. Rather the stimulus itself includes all the information, which is necessary for its recognition. For example, objects of the same height will be

partitioned at an equal ratio by the horizon line, making recognition of their common height very simple. Additionally, our own movement can be recognized by the general *optical flow* of shapes and colors around us. The optical flow can be computed in a simple way and has been proven useful for movement detection in electronic devices. For example, an ordinary optical computer mouse contains an optical flow meter based on this idea. Another idea of the ecological theory is the concept of *affordances*. According to Gibson (1979), objects are recognized not by their visual features, but rather by the possible uses of these objects. For example, a chair is not recognized because it has four legs and a backrest, but rather because it has the correct height so that we can sit on it. In this case the chair has the affordance of “sit-on-ability”. The ecological theory is mostly considered as too simplistic (e.g., Gordon, 1989), because it denies the necessity of complex computation. However, at least the concepts of affordances and optical flow are often incorporated in current theories of object perception (see e.g., Hommel et al., 2001, for a theory that uses the concept of affordances).

2.2. Action Control

There are several topics that are discussed in *action control*. First, there are two lines of thought on what causes us to act, which are widely debated. In the *sensorimotor view*, actions are assumed to be caused by external stimuli. In the *ideomotor view*, on the other hand, actions are assumed to be caused by internal goals of the person who is acting (Hommel & Nattkemper, 2011). Second, independently of the underlying cause of the action, there are theories which describe how an action may be chosen among a larger set of possible actions. Then finally as a third step the chosen action is executed, and may have to be adapted to suddenly changing circumstances. I will now give a short overview about how these three topics are addressed.

The debate whether actions are caused by external events or internal goals has been ongoing for a long time. The sensorimotor view goes back as far as Descartes (1664, cited

after Hommel et al., 2001). Similarly, the ideomotor view has been around at least since the 19th century (Lotze, 1852; cited after Hommel et al., 2001). For reasons of brevity I will not review this discussion here (see e. g., Hommel, 2009, for a review). Hommel et al. (2001), however, reason that a complete cognitive theory of actions requires combining these views. In this combined view, no goal can be formed or achieved without considering the environment, e. g., by taking into account affordances of the objects around the acting person. In other words, “Voluntary actions are reactions, too” (Hommel et al., 2001, p. 857). At the same time, most reactions to stimuli require that the person is willing to react, i. e., there needs to be a goal, or there will be no reaction. In other words, “(Most) Reactions are voluntary actions, too” (Hommel et al., 2001, p. 857). Combining these two views, Hommel et al. (2001) propose a definition of actions as “structures that link movements to goals – and vice versa” (Hommel et al., 2001, p. 857).

In order to present some ideas of how we choose to act, I will now present two theories or models that share a common underlying idea. The common idea is that both information about current stimuli as well as the chosen action are represented together, so that subsequent encounters of the stimuli can lead to fast retrieval of the previous action. This requires bindings between stimulus and action in long-term memory, however, it is not clear how these bindings are created. One hypothesis put forth here is that these bindings are not only stored in long-term memory, but also as structures in short-term memory (Giesen, 2014; Hommel, 1998). Furthermore, as I will show in Section 4.1, such routinization or automatization processes provide one of the common links between theories of action and perception and decision making. The two theories presented here are the context or exemplar model (Medin & Schaffer, 1978) and the instance theory of automaticity (Logan, 1988, 1990).

The *context* or exemplar model (Medin & Schaffer, 1978) asserts that encountered stimuli and the associated reactions are stored in memory as *exemplars*. The stimulus is encoded using all encountered features of the stimulus, regardless of whether they are

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relevant or irrelevant to the task. The reason for this is that different features can serve as a context for each other. When a new stimulus is encountered, this stimulus is compared to all other previously encountered stimuli, and the similarity to all previous stimuli is assessed. To assess this similarity, the different cue dimensions may be parameterized in a task-dependent manner. The similarity for a feature is 1 if the stimulus and the exemplar have the same feature value, and a dimension specific parameter value between 0 and 1 otherwise. For example, if a red circle stimulus \bar{t} is compared to a blue circle exemplar \bar{y} and the parameters for color and shape are c and s respectively, the total similarity would be $S(\bar{t}, \bar{y}) = c \cdot 1$ because the stimulus and exemplar have a different color but the same shape. The similarity of each exemplar to the current stimulus determines the likelihood that this exemplar will be retrieved. After a single exemplar is retrieved, the stored category or action is used. Hence, the overall likelihood of classifying a stimulus \bar{t} under a category A is

$$P(A) = \frac{\sum_{\bar{a} \in A} S(\bar{t}, \bar{a})}{\sum_{\bar{y} \in Y} S(\bar{t}, \bar{y})} \quad (2.1)$$

There are several modifications of this basic idea; for example Juslin and Persson (2002) propose the activation of multiple exemplars instead of a single one. In this case all activated exemplars are weighted and combined to form a single decision.

The *instance theory of automaticity* (Logan, 1988, 1990) tries to explain how we can act automatically and effortlessly in situations which are well known to us. The instance theory is similar to the exemplar theory in the sense that the choice of action is also based on previous encounters of similar stimuli. This theory is based on three central assumptions: *obligatory encoding*, *obligatory retrieval*, and *instance representation*. Obligatory encoding means that we automatically encode any event or item at which we direct our attention. Obligatory retrieval means that as soon as we encounter any kind of stimulus, we automatically retrieve any information that is associated with that stimulus. Finally, instance representations are the representations of previously encountered items or events, as formed by obligatory encoding and retrieved through

the process of obligatory retrieval. There may be multiple instances representing the same object, if we encountered this object multiple times. If we encounter a new stimulus, we try to retrieve a previous instance of the same problem from memory, but at the same time we also try an algorithmic strategy to solve the problem. For example, when adding single digit numbers, the algorithmic solution could be to count the fingers for each number. All stored instances and the algorithm race for the solution, and the winner of the race is used to determine the solution. As all instances have the same probability distribution of retrieval times, overall retrieval of the winner of the race will be faster with each subsequent instance (see Logan, 1988, for a mathematical derivation and proof of this fact).

These two models have in common that previous solutions to problems are stored in long-term memory as a combination of stimulus and response/decision. This means that these long-term instances or exemplars need to contain some kind of binding between stimulus features and the response. However, the feature integration theory (Treisman, 1988, see Section 2.1) only assumes bindings between features of the same object, not between stimulus and response features. It seems unlikely that the object and response features are stored separately in short-term memory but then are bound when the instances or exemplars are committed to long-term memory. Instead, it seems more plausible that object features and response features are already bound in short-term memory and are committed to long-term memory directly from short-term memory. The idea that stimulus and responses are bound together is called *stimulus-response (SR) binding* (see Henson, Eckstein, Waszak, Frings, & Horner, 2014, for a review). SR binding is one key element of my thesis and I will describe it in more detail in Section 2.3.1.

To close this section, I will now consider how actions are coordinated and carried out. Some ideas presented here are similar to ideas already described in Section 2.1 on object perception. R. A. Schmidt (1975) develops the idea that actions are carried out by performing fixed *motor programs*. These motor programs, once initiated, are

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mostly carried out without conscious feedback, although quick automatic corrections are possible (R. A. Schmidt, 1975). However, the idea of fixed motor programs, which are stored in long-term memory, introduces the problem of combinatorial explosion. Usually it is necessary to adapt our motion to surrounding factors. For example, a piano piece consists of thousands of notes, most of which are played with different length, different accentuation, etc. It would be implausible to assume that piano players have a specific motor program, for example, for playing the 15th note with the right hand of the first movement of Beethoven's Moonlight sonata. This idea seems somewhat reminiscent of the idea of a grandmother cell in object perception (see Section 2.1). To solve this problem, R. A. Schmidt (1975) develops the idea that motor programs are defined as motor schemes, which have free parameters (generalized motor program). For example, there could be a motor program for playing any note on the piano, and accentuation or length would be parameters that could be set differently for each use of this motor program. This idea was also used in the inhibition model of selective attention by Houghton and Tipper (1994). Defining motor programs as schemes with free parameters introduces a new type of binding problem. How are parameters fixed to the appropriate motor program? According to Hommel et al. (2001) motor programs and the parameters are bound into so-called action plans. There is evidence that the features of action plans are bound using mechanisms similar to those by which object features are bound, i. e., by synchronized firing of distributed cell groups (Murthy & Fetz, 1992; Singer, 1994). Furthermore, Hommel (1998, 2004) claimed that action plans are not only bound with the same mechanism, but also are bound together with the features of stimuli into an event file. The most complete theory able to explain such bindings is the theory of event coding which I describe in the following Section in more detail.

2.3. Theory of Event Coding

The *theory of event coding* (TEC) (Hommel et al., 2001) combines most of the theories presented previously into a theory of perception and action control. Furthermore, the theory of event coding also contains the idea that stimulus and response feature codes are bound together upon responding. Furthermore, it considers the actual structure of the stimulus and response feature codes (Hommel et al., 2001). The theory of event coding uses the common coding idea (Prinz, 1997) that stimulus and response features are not only bound together, but rather that the same codes are used to represent external events and actions. For example, the code for “left” could both be used to direct ones arm movement to the left side, or to represent something which is happening on the left side (Hommel, 2009). Theoretically this idea of common coding is justified by ecological reasonings, i. e., by arguments which indicate that the environment itself presents us with the information necessary for action and perception⁶. For instance, if we try to grab a cup, the distance to the cup has to be perceived and coded as a distance feature code. Then the motor program for grabbing has to be selected, and has to be bound with a feature code representing the distance to the cup. But the distance that the hand has to travel and the distance at which the cup is perceived, are the same distance in the real world. Here the real world already provides the information, which is needed as part of the motor program, there is no further need to infer this information from the information that has already been processed during perception. Furthermore, there is no reasons that the cognitive system should represent this same distance twice, once for the perceived distance and once for the distance that the hand has to travel (Hommel et al., 2001). Instead Hommel et al. (2001) uses the idea from Gibson’s ecological theory (Gibson, 1979, see Section 2.1) that this information may be reused directly. Prinz (1997) presents empirical

⁶In this sense Gibson’s 1979 theory of perception is also referred to as “ecological theory”. This theory is ecological, because it assumes that complicated processing is not required for perception, and instead the environment already contains all cues needed for perception.

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evidence that the same codes may be used to represent events in the environment and actions. For example, in one experiment participants are presented with a sequence of four arrows that they have to memorize and carry out using left and right keypresses. As soon as the first key is pressed a fifth arrow is presented that also has to be memorized and carried out as a fifth response. So responses one to four are cued in slide one and response number five is presented as soon as response number one is executed. The participants are told to carry out all five keypresses as fast as possible. Prinz (1997) found an inverted compatibility effect, i. e., participants were faster during the next keypress (number two) after the additional arrow (presented immediately after keypress number one), if the arrow pointed in the opposite direction from the one that had to be carried out at that time. However, if the arrow pointed in the same direction as keypress number two, the response was delayed. For the following keypresses (number three and four) a normal compatibility effect was shown. Prinz (1997) takes this to indicate that during perception of the arrow, the direction code is used by the perceptual system, so that it is not available for action planning. However, the perceptual processing takes place after the arrow is presented so that the direction can be memorized and appended after the four keypresses already stored in short-term memory for later execution. Hence, perception of the additional arrow happens while the participants have to execute keypress number two. This causes the inverted compatibility effect if the same code would have to be used for the coding of action and perception. Upon the following keypresses (number three and four), the perceptual processing is finished and the code for the direction of the arrow can be used as an action code. The simultaneous activation of conflicting action codes for the following keypresses causes a normal compatibility effect (Prinz, 1997).

Hommel (2009) builds on terms from Brunswik and Heider to further define the nature of the feature codes (Brunswik, 1944; Heider, 1930/1959a, 1926/1959b; cited after Hommel, 2009). Heider and Brunswik both considered the question how we can perceive the world around us in our mind. According to these authors four layers play an important role in

perception. The *distal layer* D refers to the actual objects and events in our environment. The *proximal layer* V refers to the physical information, which reaches our perceptual organs. The objects and events in the world cause a change in a medium, e. g., by reflecting light, and this medium then in turn causes a change in our perception (Heider, 1921/1999). The layer V refers to the effect which is caused by the objects or events and not the objects themselves. The layer V causes direct physiological correlates, the layer V' . Then finally from this direct sensation the mental representation of the objects is constructed in the layer D' (Heider, 1930/1959a; cited after Hommel, 2009). One of the main challenges is to explain, how D and D' can correspond to each other, although neither D and V nor V' and D' directly correspond to each other (Hommel, 2009), but rather have an information/medium relationship. Brunswik (1944, cited after Hommel, 2009) adapted this model also for actions. In terms of actions, the distal effect is the goal that one is trying to achieve with the given action, whereas the proximal muscle commands are only a means to achieve it. Furthermore, Hommel et al. (2001) divide the effects of our actions into *proximal* and *distal effects*. For example, when switching on the light, the proximate effect would be the direct sensation of the switch pressing against the finger etc. The distal effect on the other hand, would be that we perceive the room to go from dark to light (Hommel, 2009; Hommel et al., 2001). Hommel et al. (2001) point to various variations of the Simon task as evidence that we encode distal and not proximate effects. For instance, the Simon effect remains stable with respect to key position, if the hands are crossed (Wallace, 1971, 1972), or even if the keys are pressed using parallel or crossed sticks (Riggio, de Gonzaga Gawryszewski, & Umiltà, 1986). All this indicates that the Simon effect is caused by the relation between the stimulus and the distal key position, and not by the proximate hand position (Hommel et al., 2001). At the same time the distal effects usually coincide with the goals we have while carrying out an action. If we try to switch on a light, and the light bulb is broken, we will most likely not be satisfied

by the feeling of the switch against our finger, as the intended goal is the sensation of light (Hommel et al., 2001).

The theory of event coding builds upon the feature integration theory (Treisman, 1988), and also includes binding mechanisms. While the feature integration theory only considers bindings between stimulus features, in the theory of event coding, this idea is generalized to bindings between stimulus and response features as well. Since stimulus and response features may share a common coding domain, this means, that codes may be re-used for stimulus and response domains. However, the idea of purely visual bindings is also still maintained. Hommel and Colzato (2009) indicate that two binding mechanisms exist. *Visual integration*, on the one hand, which is driven by convergence and can use previous knowledge about existing conjunctions. *Visuomotor integration* on the other hand is driven by neural synchronization and is oblivious to learned conjunctions. Response features are only included during visuomotor integration, but not during visual integration. During visuomotor integration, any action related information is bound, including activation conditions, context, actions and action effects or even thoughts that accompany the event (Hommel, 2009). The integration is done on a temporal basis, i. e., any feature that accompanies the event in time, is integrated. The visuomotor integration process, produces an event file, which is a complete episodic trace of the event, similar to object files, which are traces of the object.

Haazebroek and Hommel (2009a, p. 43ff) give an example of how the theory of event coding can be applied to a simple driving task. In this example s_i denotes sensory codes, f_i denotes feature codes, m_i denotes motor codes and e_i denotes event files. This example assumes that the person who is driving has never driven before. The first step is that the person experiences the effects of the different pedals. So the person learns that pressing the right pedal results in a forward motion and the left pedal stops the car. This creates an association or binding between f_{forward} and m_1 (motor code for pressing the right pedal) and between f_{stop} and m_2 (motor code for pressing the left

pedal). The next step is that the driving instructor tells the driver that he should stop when he sees a red light, and that he may drive if it is green. This creates two event files, $e_{\text{stop for red light}}$ and $e_{\text{go at green light}}$ (Haazebroek & Hommel, 2009a; see also Pfeuffer, Moutsopoulou, Pfister, Waszak, & Kiesel, 2014). The event file $e_{\text{stop for red light}}$ contains the binding of f_{red} , $f_{\text{traffic light}}$, f_{stop} and the other binds f_{green} , $f_{\text{traffic light}}$, f_{forward} (Haazebroek & Hommel, 2009a). Neither of those event files contains any motor or sensory codes. Both event files are now activated, which increases attention to any of those features, which are contained in them. Furthermore, the corresponding feature dimensions, color and motion are weighted as well, in order to increase attention to those dimensions. Also, all features associated to traffic lights are activated, for example if there is a learned association between $f_{\text{traffic light}}$ and $f_{\text{side of road}}$, which represents knowledge about the normal location of traffic lights, then $f_{\text{side of road}}$ is activated as well. This increases attention to any kind of object appearing at the side of the road. When the driver approaches the first intersection with a red traffic light, all sensory codes representing stimuli present at this intersection are activated. The previous activation of $f_{\text{traffic light}}$ and $f_{\text{side of road}}$, however, serves as a top down control, which makes the driver especially sensitive to traffic lights. Thus the additional activation that the $f_{\text{traffic light}}$ code receives is forwarded to both event files. The activation from the f_{red} feature code is only forwarded to the $e_{\text{stop for red light}}$ event file leading to further activation of the codes contained within this event file. Since this event file contains the feature code f_{stop} this code is activated and leads to activation of the m_2 motor program (see Haazebroek & Hommel, 2009a, for a more detailed version of this example).

In the next section, I will summarize some of the findings for binding and retrieval of relevant stimulus feature codes and response feature codes. After that, I will look at the empirical evidence that even task-irrelevant stimulus feature codes can be integrated in an event file.

2.3.1. Stimulus-Response Binding

One of the main effects, which has been used to study perceptual processes, is *priming*. Priming refers to changes in accuracy, bias or reaction time when responding to a stimulus after the same or a similar stimulus has been presented (Henson et al., 2014). A first explanation for *priming effects* was that component processes are facilitated by the prior presentation of the stimulus (Roediger, Weldo, & Challis, 1989). However, this explanation is insufficient to explain several priming effects, e. g., negative priming, so that newer explanations assume that bindings between stimulus and response (*SR bindings*) are created, which cause the priming effects (Henson et al., 2014). SR binding can be explained by many theories, e. g., by the theory of event coding (Hommel et al., 2001) or by the instance theory of automaticity (Logan, 1988). Because it integrates many other theories, in this thesis, I will use the theory of event coding (Hommel et al., 2001) as the theoretical foundation.

Empirical evidence for SR binding was gathered by different priming paradigms (Damian, 2001; Logan, 1990; Rothermund et al., 2005; see also Henson et al., 2014, for an extensive review). Furthermore, it could be shown that SR bindings occur not only in the visual modality (Hommel, 1998) but also in the auditory (Leboe, Mondor, & Leboe, 2006; Zmigrod & Hommel, 2009), tactile (Zmigrod, Spapé, & Hommel, 2009), and even across modalities (Zmigrod et al., 2009). Furthermore, it was demonstrated that SR bindings survive task switches (Pösse, Waszak, & Hommel, 2006).

Note that not only tasks in which simple classifications, e. g., if a line is horizontal or vertical (Hommel, 1998), are used to test SR binding but also tasks where the stimuli and the response are more complex. For example, Dobbins, Schnyer, Verfaellie, and Schacter (2004) presented pictures to participants and asked, whether the displayed object was larger than a shoebox. Furthermore, in some trials, the task was switched, i. e., participants had to indicate whether the object was smaller than a shoebox. priming effects, in form of decreased response times, were found for repeated objects even in the switched tasks.

Schnyer et al. (2007) used a similar setup as Dobbins et al. (2004), but also included different objects for each category. Priming effects were found across response switches, as well as for repeated objects or objects from the same category. However, priming effects were reduced for objects from the same category in comparison to the same object. Furthermore, priming effects were reduced when the response was switched, only for repetition of the same object. An analysis including similarity ratings for objects from the same category indicated that items with higher similarity ratings caused stronger priming effects. These findings are interpreted by Schnyer et al. (2007), that not the response given to the previous encounter is bound, but the decision. Denkinger and Koutstaal (2009) also present evidence that priming is consistent across different objects from the same object category. Horner and Henson (2011) went even further and could show that pictures can be used to retrieve bindings formed by the presentation of words and vice versa. Horner and Henson (2009) found evidence that multiple hierarchical response codes are bound simultaneously. For example, if participants have to decide, whether an object is larger than a shoe-box, during priming and are later asked whether an object is smaller than a shoe-box, they are faster for previously primed object than unprimed objects. However, if they are asked, whether an object is man-made, there is no speed up for primed objects. Horner and Henson (2009) conclude that the classification (larger/smaller than a shoe-box) of the object is bound with the stimulus. When the stimulus is later encountered again the classification can be retrieved, so that any comparison with a shoebox is speeded up. In another experiment, they disentangled the classification and the decision by changing the reference object of the comparison. For example, participants were primed with tasks, in which they had to compare an object to a shoe-box. Then in the probe trials, they had to compare the objects either to a pencil case or a wheelie bin. Simultaneously, while in the prime they were asked if the object was bigger than a shoe-box, in the probe trials they were both asked if the object was bigger or smaller than the given reference object. This way they could vary the classification (larger/smaller

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than reference object) and the decision (yes/no) orthogonally, leading to combinations of classification congruent/incongruent and decision congruent/incongruent probe trials. They found a facilitation for repeated objects both in the decision congruent as well as in the classification congruent trials. However, there was less facilitation for the incongruent trials. They interpret this evidence that both the classification, as well as the yes/no decision are bound with the stimulus. Also there was no interaction between classification congruency and decision congruency, indicating that the decision and the classification are bound independently. It should be noted, that the term decision used here is not the same as the one used in the field of decision making. While in decision making, the focus lies on the actual processes involved, e. g., the heuristics which are used (Bröder & Schiffer, 2006), here this term refers to the the result produced from a simple classification, e. g., “Is the object bigger than a shoe-box”, which can almost directly be derived from memory, so that there is only little to no inference required (see also Chapter 3). When looking at the processes required, comparing an object to a shoe-box or to a wheelie bin should not be considered the same decision, as the reference object was changed, even if both result in the same “yes” or “no” answer. Also, the idea that a response production can be separated into perception, classification, decision and action in that order should only be seen as a description which fits some of the experiments done by Horner and Henson (2009, see also Horner, & Henson, 2011). In one of the experiments participants just had to vocalize the name. Horner and Henson (2009) describe the identification of the object as the decision performed during this task, but in this case it is not clear, what the classification for this task would be. Still, the evidence put forth by Horner and Henson (2009, see also Horner, & Henson, 2011) indicates that multiple levels of response codes can be bound independently. In their case, the bound codes were classification, decision, and action codes. However, because of the difference in the nature of the tasks used in binding research, different tasks may require different levels. Because of the nature of the tasks used in this thesis for example, the tasks only require decisions (which however are

closer to the classifications of Horner and Henson, 2009) and actions but no classifications. These components will be disentangled empirically in Experiment 3c.

This research considered only task-relevant stimuli. However, the theory of event coding is not limited to relevant stimuli so that under this theory even irrelevant stimuli can be bound in an event file (Hommel, 1998). Still, task-relevant dimensions are weighted higher than task-irrelevant dimensions. The task-irrelevant dimensions will be activated, just not as strongly. Task-irrelevant stimulus features can trigger an event file depending on how perceptually salient they are (Hommel, 2004, 2005; Hommel & Colzato, 2004). In the following Section I will discuss empirical evidence for integration of task-irrelevant features in an event file.

2.3.2. Distractor-Response Binding

As described in the previous section, Hommel (1998, see also Hommel, 2004, 2005; Hommel, & Colzato, 2004) demonstrated that irrelevant stimulus features can be bound in an event file. By using a modification of the negative priming paradigm, Rothermund et al. (2005) could also show that distractors are bound together with the response (cf. Giesen & Rothermund, 2014, for evidence, that the target is bound as well). The distractor is even included in the binding if distractor and target are separate objects, e. g., the flanking “J”s in the letter string “JFJ” as part of a flanker task (Rothermund et al., 2005; experiment 4 Frings et al., 2007); or for irrelevant words (Giesen & Rothermund, 2011). The negative priming effect here was found to be modulated on a response repetition. This can be taken as evidence that the negative priming is not caused by inhibition of the distractors, but rather that the response is retrieved, as predicted by the theory of event coding. Frings et al. (2007) further varied the paradigm by investigating distractor-to-distractor repetitions more closely, introducing the distractor-to-distractor priming paradigm (see Figure 2.1 on page 15 and the corresponding explanation at the beginning of this chapter). By varying this paradigm it was shown that *distractor-response binding*

not only occurs in the visual modality (e. g., Frings, 2011) but also in the auditory modality (Moeller, Rothermund, & Frings, 2012; but cf. Mayr & Buchner, 2006; Mayr, Buchner, & Dentale, 2009, for a different approach), the tactile modality (Moeller & Frings, 2011), and across different modalities (Frings, Moeller, & Rothermund, 2013). Furthermore, distractor-based response retrieval has been observed with different tasks such as with location tasks (Frings & Moeller, 2010), across different tasks (Forstmann, Brass, & Koch, 2007; Rothermund et al., 2005), and can even influence driving behavior outside the lab (Moeller & Frings, 2014b).

Nevertheless, distractor-response binding also has constraints. For example, distractors are neither bound with the response when they are not attended (Moeller & Frings, 2014a), nor are they bound if they are from a different semantic category (Giesen & Rothermund, 2011), or spatially separated (Frings & Rothermund, 2011). Also, the distractors have to be presented shortly before or simultaneously with the target (Frings & Moeller, 2012). Thus, to bind the distractor in an event file, the distractor has to be perceived as belonging to the target. An additional factor that hampers distractor-response binding is stress (Frings, Larra, Gräbener, Moeller, & Schächinger, 2013).

Current theories indicate that distractor-response binding is part of stimulus-response learning, which is seen as a basis of instance or exemplar learning (Giesen, 2014; Hommel, 1998; Moeller & Frings, 2014c, see also Section 4.1.1). Distractor-response binding seems to be a mechanism, by which additional contingent features are learned that can speed up recognition, by binding classifications and decisions, as well as action, by binding previous responses to the stimulus. For example, while a predator may be mainly recognized by the body shape, associating the fur with the flight response can potentially speed up the flight response (Moeller & Frings, 2014c). Hence, inclusion of distractors in event files as part of the distractor-response binding effect allows for learning of additional features for faster recognition. In this case, it would not be sensible to include features in an event file, for which long-term bindings already exists. Moeller and Frings (2014c) showed that

previous existing task-related long-term associations could prohibit binding of irrelevant features.

However, besides these constraints distractor-response binding is a rather robust phenomenon. The cited evidence demonstrates that distractor-based retrieval processes influence a variety of tasks. This raises the question if not only responses can be influenced but also decisions. In the following Chapter, I will summarize some findings which show that not only in perception-action control irrelevant information influences behavior, but also in the area of decision making. This leads to the comparison of theoretical similarities in perception-action control and decision making. Consequently, I will conclude that distractor-based retrieval processes also play a role in decision making⁷. If this hypothesis can be empirically supported, the same cognitive mechanism as defined in the theory of event coding should be assumed.

⁷Note that I take distractor-response binding as a special case of SR bindings. Therefore, I assume that the findings I can present for distractor-response binding can be generalized to other kinds of SR binding. Because of that I use the terms SR binding and distractor-response binding interchangeably when I consider them for my findings.

3. Irrelevant Information in Decision Making

When we judge or decide without knowing the correct answer, we often have to infer the correct decision from relevant and available information (Gigerenzer & Goldstein, 1996). The possible choices are called the *options* of the decision, while the bits of information we have available for deciding between these options are called *cues*. Choosing one of the options results in a consequence, the outcome of the chosen option. For instance, imagine you are trading at the stock market. You own some shares of a large publishing company. You are currently deciding whether to keep or sell these shares. In this example your options are the actions “keep” and “sell”. On the one hand, if you decide to keep the shares and the value rises, the financial gain is the outcome of your decision. On the other hand, if the shares fall, the money you lost is also the outcome of your decision. Imagine you also know that this company is publishing a book that will be released as a movie in a few days, which may increase the value of the shares. Your knowledge about the upcoming movie release is a cue, which indicates that you should keep your shares. However, you also know that the board of the company has just recently made a few bad decisions which may reduce the value. Your knowledge about the previous bad decisions also is a cue; this time it is a cue that indicates you should sell. A book turned into a movie *may* increase the profit, but sometimes it may not. Also knowing that the management has decided badly, indicates that the price will drop only with a certain probability. Hence, this task is a *probabilistic decision* task. A probabilistic decision task

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is a task, where the outcome for at least one of the options is uncertain and only known with some probability. The goal of a decision task is to choose the option, which has the best outcome. The probability with which a cue indicates that an option is the correct one, is called the *validity* of the cue (Bröder, 2009; Gigerenzer & Goldstein, 1996).

If a cue does not indicate the correct option, it is irrelevant for the decision. It is reasonable to expect that nobody would knowingly consider irrelevant cues or other irrelevant information when making a decision. Furthermore, in decision making research of multi-cue/multi-attribute decision situations, it is claimed that even relevant cues are ignored to decide efficiently (Gigerenzer & Brighton, 2009; Gigerenzer & Goldstein, 1996; Gigerenzer & Todd, 1999; Todd & Gigerenzer, 2012). Therefore, people use fast and frugal heuristics (Gigerenzer & Todd, 1999). For instance, the *take the best heuristic* assumes that decision-makers only use the cue with the highest validity, which indicates the correct option, and decide in accordance with that cue. All other cues, even if they indicate another option than the most valid cue, are ignored (Gigerenzer & Goldstein, 1996).

However, in fact, in the literature on decision making several effects of irrelevant information on decision making have been reported (Huber et al., 1982; Nisbett et al., 1981; Platzer & Bröder, 2012; Tversky & Kahneman, 1974, 1981). For example, Nisbett et al. (1981) showed that people who get mixed information – relevant and irrelevant – make less extreme predictions than people who only get relevant information. This is called the *dilution effect*. Participants who have to judge a fictive person made less extreme judgments if they had irrelevant information in addition to relevant information than if they had only had relevant one (Nisbett et al., 1981). The dilution effect also occurs in Bayesian beliefs (Jenny, 2013). When participants got samples of cards drawn from different decks, which also included non-diagnostic cards, they made less extreme predictions than participants who received only samples of diagnostic cards. Another well-known effect where irrelevant information influences judgments is the *anchoring*

effect (Tversky & Kahneman, 1974). The anchoring effect describes the phenomenon in which people's final judgment is biased towards a given arbitrary number – the anchor. Thus, people use an arbitrarily chosen reference point for their value estimates, but they adjust their value estimates insufficiently away from the reference point towards the true value. The arbitrary reference point influences the judgment even if it is clear that the anchor provides no valid information for the judgment (e.g., Mussweiler & Strack, 2001; Tversky & Kahneman, 1974). Other effects which deal with the influence of irrelevant information are the framing effect (Tversky & Kahneman, 1981) and the decoy effect (Huber et al., 1982). The *framing effect* describes the phenomenon that people change their preferences depending if the exact same outcomes are presented as losses or gains (Tversky & Kahneman, 1981). For instance, if the descriptions of a prevention program against an Asian disease focused on the survivors, participants chose the option more often, which only had one single certain outcome. On the other hand, if the descriptions focus on the fatalities, the participants tended to decide for the option, which had multiple uncertain outcomes. That is, participants did not take a risk, if this risk would indicate that they might reduce the number of survivors. However, they took their chances, if this could reduce the number of fatalities. The *decoy effect* also demonstrates how people change their preferences. In a preferential two-attribute decision task, where each option dominates another option along one of the cues, people tend to decide for each option with equal probability (Huber et al., 1982). However, if a third option is added, which dominates the first option on one of the cues, but not the second cue, while simultaneously being dominated by the second option on both cues, people tend to decide for the second option more often (Huber et al., 1982). For example, if one has to decide between two car models, one of which (model A) has a great gas-mileage but also a high price, whereas the other (model B) has a bad gas-mileage and a low price, then people tend to decide with equal probability between both models. However, if a third car model (model C) is added to the decision situation, which has a somewhat

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higher price than model B (it is dominated by model B but dominates model A) and a somewhat worse gas-mileage than model B (it is dominated by model A as well as by model B), then people will tend to choose model B. Here the third option is irrelevant to the decision situation as it would never be chosen when compared with the option that dominates it. Nevertheless, people's choices are influenced by addition of this irrelevant option.

More relevant for the scope of this thesis is the finding that people included irrelevant cues in their judgments if the cue is presented saliently and therefore easy to retrieve from memory (Platzer & Bröder, 2012). Thus, irrelevant cues, which are easily accessible, seem to demand the same cognitive effort to ignore as if to integrate in the decision process (Platzer & Bröder, 2012; Platzer, Bröder, & Heck, 2013).

Furthermore, Khader et al. (2011) showed that even if participants are explicitly instructed to use the take the best heuristic (Gigerenzer & Goldstein, 1996) they at least consider other presented information. In addition, Kusev et al. (2012) showed an influence of the previous task on the current one. The previous tasks could activate concepts which would then influence the decision in the current task; that is, participants were more likely to decide for an insurance against car theft if they had to decide in the previous task whether there were more car thefts in London or New York, than if the previous task asked about accidents. These findings could be explained by the theory of event coding (see Section 2.3 on page 35). In this case the first task would create a event file containing a connection between cars and robberies. Then when the next question about cars is presented, this existing event file is retrieved, causing the participants to decide for an insurance against car theft. Event files may be created for many reasons, for example, event files may be created by performing an action (Hommel, 1998, 2007; Hommel & Colzato, 2004), planning an action without executing it (Stoet & Hommel, 1999) as well as through instructions (Haazebroek & Hommel, 2009a; Hommel, Colzato, & Van Den Wildenberg, 2009; Pfeuffer et al., 2014). Similarly, event files may serve multiple

purposes, for example as episodic memory traces and as task representations (Haazebroek & Hommel, 2009a; Hommel et al., 2009). Thus, it seems likely, that event files are just general structures for storing acquired knowledge. In this case, thinking about cars and robberies simultaneously, would create an event file, as hypothesized above, which may later be retrieved. A different explanation for the finding by Kusev et al. (2012) could be, that the first task simply activates the concept of robberies, which then has a higher availability when the next decision has to be performed. A possible way to distinguish between these two explanations would be, to have the participants not only decide about insurances for car thefts, but also for insurances about break-ins. A higher activation of the concept of robberies in general, should lead to an increased rate of decisions for insurances in both cases, whereas the theory of event coding specifically predicts a higher rate for car insurances but not for insurances against break-ins.

In the realm of decision making the influence from the previous trial to the next one has been neglected until now. However, in the experiments I will show that the presented information in a previous decision task can influence the following one as predicted by the distractor-response binding effect. Furthermore, to indicate a common underlying basis of decision making and perception/action, in the next chapter I will point out theoretical similarities in decision making and perception/action.

4. Links Between Perception and Decision Making

As indicated in the introduction, one major step to bring together the fields of perception and action and decision making, is to show currently existing theoretic parallels between these two fields. Hence, in this chapter, I will present some theories and models for both decision making and perception and action, which can serve as such a link. Moreover, I will focus on theories, which are related to distractor-response binding.

In Section 4.1 I will look at routines and automatization, and show how these two concepts can be found in both decision making as well as in perception and action. Since event files have been linked to automatization (Giesen, 2014; Hommel, 1998), the underlying hypothesis here is that event files are the underlying mechanism for both routine establishment as well as learning of automated actions. In Section 4.2 I will introduce a computational model for the theory of event coding (Section 4.2.1) as well as a computational model for decision making (Section 4.2.2). I will then compare these two models, to identify points of convergence between both fields (Section 4.2.3).

4.1. Routines and Automatization

In day-to-day life decisions are usually not made in a one shot fashion, but have to be repeated multiple times. For example, the meal choice at the cafeteria has to be repeated every workday. Of course, the potentially costly (in terms of time and cognitive resources)

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inference is not done every time we encounter a problem we have already solved. Instead recurrent decisions are approached using routines, which have been build up during previous decision situations (Betsch, Haberstroh, & Hohle, 2002). Betsch et al. (2002, p. 456, emphasis in the original text) define *routines* as an “*option that comes to mind as a solution when the decision-maker recognized a particular decision problem [. . .]*”. According to this definition, a routine refers to a particular behavior or behavioral sequence that is dominantly associated with a mental representation of a decision problem.” This definition only requires that the routinized option is activated, not that it is actually chosen; in this respect routines differ from habits (Betsch et al., 2002).

Similarly to decisions, when we repeatedly respond in the same way to a stimulus, we also get faster with more practice (Newell & Rosenbloom, 1981). Likewise, the effect of practice can be shown both for tasks requiring mainly perception, e. g., identifying a single target letter within a set of distractors, or tasks mainly requiring motoric behavior, e. g., positioning a cursor on the screen onto a target by using a joystick or the keyboard (Newell & Rosenbloom, 1981). Logan (1988) refers to the kind of behavior achieved after practice as automatic behavior. The instance theory of automaticity aims at explaining how this automatic behavior works (Logan, 1988, 1990). Automatic behavior is characterized by being fast, effortless, and does not require attention (Logan, 1990).

Based on the similarity of both concepts, it is plausible that automatization and routines both refer to the same type of behavior, i. e., a behavior which has become automatic due to sufficient practice and repetitions. One fundamental question is then, whether routines in decision making and automatization for perception and action control are driven by the same mechanisms, or if different mechanisms are used. If the same mechanisms are used, this would imply that the same effects that have been found for automatization also apply to decisions, and vice versa. Some experimental evidence for similar mechanisms already exists. For example, learning, both if motoric actions are learned, if perceptions are learned, as well as for learning of decisions and problem solving, always follows a

power law (Newell & Rosenbloom, 1981). This power law can be explained by the instance theory of automaticity (Logan, 1988). Furthermore, this theory can be linked to the theory of event coding (e. g., Giesen, 2014; Moeller, 2011), although experimental evaluation of this link is still ongoing. If both routinization in decision making and automatization is achieved by the mechanisms proposed as part of the instance theory of automaticity, and the event files are a necessary part of this mechanism as well, this would imply that event file mechanisms and the resulting effects can also be found for decision making. This may also give further insight into the memory structures, which lead to routines.

In the following sections I will give an overview of some of the ideas about routines and automatic behavior in action and perception (Section 4.1.1) and in decision making (Section 4.1.2). I will then give a short overview of the parallels and differences in both theories (Section 4.1.3).

4.1.1. Event Files and Automatization

To see, if the theoretical concepts explaining automatization can be applied to decision making, it is first necessary to give a short overview of these theories. In this overview I will focus on the links between the instance theory of automaticity and the theory of event coding.

According to Logan (1990, see also Section 2.2), all stimuli that are encountered and whatever is associated with them, are automatically encoded in memory to be retrieved at subsequent encounters. Similar ideas also underly the context model (Medin & Schaffer, 1978) and the recognition primed decision model (RPD, see Logan, 1990). There is a close relationship of all these models of automaticity and the theory of event coding, in the sense that both rely on bindings of stimuli to associations or responses. Hommel (1998, see also Giesen, 2014) reasons that event files may be the same as instances. In that case, acquired knowledge would first be stored in an event file for retrieval in subsequent trials, but also be committed to long-term memory as an instance or exemplar representation

of the encountered event. One important difference, though, is that Logan (1990, see also Hommel, 1998) assumes instances to require attention to be stored¹, and this would exclude irrelevant information from being encoded. The context model, on the other hand, does not presuppose attention for the storage of exemplars, hence, this would be in line with the findings of Hommel (1998) and with distractor-response binding in general (however cf. Moeller & Frings, 2014a, for a contradictory finding). There is more evidence that seemingly irrelevant information is encoded together with the response. J. R. Schmidt (2013) proposes contingency learning as an alternative explanation for the proportion congruent and Gratton effect (Gratton, Coles, & Donchin, 1992). The *proportion congruent effect* arises when the number of congruent and incongruent trials differs within a Stroop task. In case there are more congruent than incongruent trials, the Stroop effect is increased compared to experiments where there are more incongruent than congruent trials. J. R. Schmidt (2013) explains this effect by indicating that if there are more congruent trials, the word to be ignored is more regularly paired with the corresponding color, i. e., an artificial contingency between word and text color is created. In that case participants may learn the word as cue for the color, and hence respond faster in congruent trials. On the other hand, if there are more incongruent trials, the word must be paired more frequently with a different color, than with the same color. In case of a two choice Stroop task, for example, the word correlates with the opposite color (the pairing used in incongruent trials), making it a contingent cue for the opposite color (J. R. Schmidt, 2013)². The same reasoning can be applied to the *Gratton effect*. The *Gratton effect* manifests in a difference in strength of congruency effects in trials

¹At least for the strong version of the instance theory of automaticity (Logan & Etherton, 1994).

²It should be noted, however that in the terminology of decision making, this turns the word into a valid cue for the color. Contingency implies that the validity (at least for two choice situations) must be above $v = .50$, so that in the terminology used in this thesis, a color word in an unbalanced Stroop task is a relevant and not an irrelevant cue (see also Chapter 3)

following a congruent compared to trials following an incongruent trial. In trials following congruent trials a larger congruency effect is observed compared to trials following an incongruent trial. In many cases, this effect can be explained by distractor-response binding. Congruent trials following a congruent trial will either be DC-RC or DR-RR trials (see Figure 2.1 on page 15). On the other hand, incongruent trials following a congruent trial can be either DR-RC, DC-RR or DC-RC trials³. The different possibilities for intertrial relations lead to a speed up of congruent trials following congruent trials. A similar reasoning can be applied to trials following incongruent trials (J. R. Schmidt, 2013). In order to exclude such binding effects, it is necessary to exclude trials in which either the color or the color word is repeated. However this introduces a contingency effect, so that according to J. R. Schmidt (2013) the *Gratton effect* can be explained by a combination of binding effects and contingency learning. Contingency effects, however, are statistical effects that cannot be learned from single trials, at least not reliably. While features of the current trial may prove to be helpful later on due to contingency effects, this cannot be determined during the current trial. In order to detect contingencies, seemingly irrelevant information must be encoded together with relevant information, to be later retrieved and tested for contingency. While such an encoding of seemingly irrelevant and hence likely unattended information is not part of Logan's instance theory of automaticity (Logan, 1990), encoding of currently deemed irrelevant information is part of the context model (Medin & Schaffer, 1978), so that this model may be better suited for explaining contingency effects.

³Take, for example, a trial in which the word "Blue" is presented in blue. A following congruent trial can either present the same color word combination again (DR-RR) or a different combination of congruent color and word (DC-RC). A following incongruent trial on the other hand could present the word "Blue" in a different color (DR-RC), a different blue colored color word (DC-RR) or a completely different incongruent combination (DC-RC).

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This reasoning indicates that event files may be an inherent part of the learning mechanisms used for contingency learning. In this case, it would not be subjectively irrelevant information which is included in the event file, but rather information whose relevance cannot be determined, yet. One objection one may point out here, is that in most experiments conducted on distractor-response binding, the participants were told that the irrelevant stimulus was irrelevant and to be ignored. However, the description experience gap (Hertwig & Erev, 2009) shows that information which is told to participants is processed differently from information which is learned directly. Although the description experience gap was discovered for decision experiments, the links between perception and decision making makes it seem likely that a similar effect also plays a role here. Hence, the information given by the experimenter about the relevance of the stimulus may not be fully used, so that contingency learning still took place.

Further, evidence exists, which can link event files and contingency learning. First, in the case of contingency learning, one would expect that information which has been previously learned to be irrelevant is excluded. Hence, previous knowledge about the cues may influence binding processes. Moeller and Frings (2014c) could show, that distractors are not bound, if they have long-term association to task-relevant features. For example, if participants have to respond with left and right keypresses, and the distractors consist of left and right arrows, the distractor-response binding effects were reduced in trials with incompatible primes, i. e., trials where the arrows pointed in the other direction than the one on which the response had to be made in the prime. One possible explanation is that the existing long term association between the arrow and the direction hampered creation of the event file. Another possible explanation put forth by Moeller and Frings (2014c) is that the observed effects may be produced by the Gratton effect, a possible confound in the experimental design. As J. R. Schmidt (2013) points out, though, the Gratton effect may only be caused by contingency and binding effects, so that an explanation of these effects based on the Gratton effect may be the same as explaining the effect by

a binding account. In contrast, Colzato, Raffone, and Hommel (2006) found evidence against event files as mechanisms for contingency learning. They manipulated contingency in the training trials and found no effect of contingency on the strength of binding in later experimental trials, thus questioning the relationship between binding and learning. In this set of experiments, they introduced a contingency between the irrelevant feature color, and the relevant shape feature (and by transitivity also response). Later studies indicate, though that event files are driven by two separate binding mechanisms. First, stimuli are bound into object files, and then these object files (visual integration) are integrated with the response into event files (visuomotor integration) (Hommel & Colzato, 2009; see also Frings & Rothermund, 2011). Hommel and Colzato (2009, see also Colzato et al., 2006; Hommel, 1998) indicate that color may play a special role, because if color appears as a task-irrelevant feature, it only takes part in visual integration, but not in visuomotor integration. However, routinization or automatization is mainly useful for efficient selection of responses, hence one would expect these mechanisms to rely on products from visuomotor integration and not from visual integration. Since color does not take part in visuomotor integration, the lack of evidence of learning effects for binding processes found by Colzato et al. (2006) may be due to shortcomings in the experimental design.

In the following section I will give a short overview about research on routines in decision making. After this section I will conclude with a short comparison between the research in both fields.

4.1.2. Recurrent and Routinized Decision Making

Betsch et al. (2002) give an overview of effects which are caused by routines, as well as an extensive evaluation how different theories of decision making could explain routines. If routines and automatization are driven by similar or even the same mechanisms, it should be possible to also identify these effects for basic perception tasks. The main effects

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of routines are as follows (see Betsch et al., 2002, for a full review): (1) Identification of the type of decision situation causes activation of the routine. (2) Recognition of a decision situation can cause selection of the routinized option. (3) The stronger the routine, i. e., the more often the routinized behavior has been performed, the more likely is the routinized option chosen. (4) The depth of the information search is decreased with stronger routines. (5) Stronger routines cause less elaborate information searches. (6) The stronger the routine, the more confirmatory information will be searched. (7) For stronger routines, contradictory information has less impact. This effect is stronger under time pressure, but also appears in unconstrained situations. (8) The likelihood of using the routine depends on context factors: (8a) Time pressure causes more routine choices. (8b) Perceived novelty causes routine deviations. (9) The influence of routines on the behavior is mostly independent from intentions. (10) The stronger the routine, the less intentions can cause a routine deviation. Bröder, Glöckner, Betsch, Link, and Ettl (2013) present evidence that routinization is not limited to options. Thus, people do not only learn that a single option may pay off better in subsequent decisions, but they also learn that some strategies may be better suited to some type of problem than others. However, the formation of option or strategy routines seems to depend on many factors, e. g., presentation format (Bröder et al., 2013).

Routinization introduces additional problems in comparison to normative solutions. In recurrent decisions, learning of cue validities, payoff structures, and routines has to be intertwined. This may lead to inefficient routines. Consider, for example, two lotteries, one which always pays 1€ ($U = 1 \cdot 1 = 1$) for each play, and one that pays 1 000 000€ with a chance of .01% ($U = .0001 \cdot 1\,000\,000 = 100$). On average the big win from the second lottery will require 10 000 plays, so for a long time this lottery will look like a worse strategy than the other. Somebody who has to repeatedly choose between those two lotteries will sooner or later develop a routine that consists of choosing the first lottery over and over again. But, in the long run this routine will provide a worse payoff than

choosing the second lottery repeatedly. Since the decision-maker does not know the payoff structure, there is no way to know that this big payoff will eventually happen. If we assume on the other hand that no learning and routine formation takes place, the decision-maker will have to choose randomly each time, which means after about 20 000 plays (10 000 on the first and 10 000 on the second lottery), he will eventually hit the big payoff from the second lottery. So routine formation and memory prove maladaptive in this case. However, the reason that the routine is maladaptive in this case, lies in the problem structure. If we instead consider a second lottery that simply never pays off, the same routine is well adapted. Instead now the solution without memory or routinization will decrease the total payoff. Unfortunately for the decision-maker, these two cases are indistinguishable for a large number of trials (up to about 10000). Using a routine or other kinds of previously learned knowledge is referred to as *exploitation*, whereas choosing a new option or trying to acquire new knowledge is called *exploration* (Gupta, Smith, & Shalley, 2006; March, 1991). Pure exploitation strategies tend to get stuck in stable suboptimal routines, whereas pure exploration strategies do not use knowledge efficiently (March, 1991). In order to be efficient a decision-maker should use both exploration as well as exploitation. This is called the *exploration/exploitation trade-off* (March, 1991). However, there is no rational theory, which can explain how much exploration and how much exploitation behavior should be used in such situations. Rather, the optimal behavior mostly depends on assumptions about the future payoff, which cannot be validated (Barron & Erev, 2003). A. S. Luchins (1942, see also A. S. Luchins, & E. H. Luchins, 1959) showed that people perform mostly exploitation behavior, and little exploration. This tendency is stable, even if simpler solutions could be derived by rethinking a previous solution or if the immediate previous problem unexpectedly failed when attempted using the previously learned routine (A. S. Luchins, 1942).

I will now compare both the theories of routinization as well as those for automatic behavior to identify a common basis and further motivate the research presented in this thesis.

4.1.3. Comparison of Theories of Automatization in Perception and Decision Making

The previous sections show that a common basis for decision making and perception on the basis of routines can be identified. While the instance theory of automaticity has mainly been used for explaining automatic behavior in basic classification tasks, it has been linked to decision making before (Johnson & Busemeyer, 2005). The current research and theories show that event files likely are part of the mechanism, which leads to the memory structures used for automatic behavior. However, the link mainly relies on statistical contingency effects. Event files, at least if they bind irrelevant or distractor information, allow us to identify a correlation between these distractors and the given response. This further means that event files are in this case not used for binding reliable information, which can directly be used for selecting the correct response, but rather information which first requires some kind of inference mechanism. Hence, this indicates that event files may be part of a mechanism used for gathering information, which can later be used for probabilistic decisions. The fundamental hypothesis of this thesis is that decisions and perception are based on the same structures. If this hypothesis is true event files should not only be a part of decision processes, of which we are unaware, such as in basic perception, but also of probabilistic inferences, when we are aware that we are currently deciding. A similar reasoning applies, if one assumes that automatization is performed in the way indicated by the context model, since both the context model as well as the instance theory of automaticity require bindings between decisions or actions and stimuli or cues.

On the other hand, to test if the instance theory of automaticity or the context model could explain the findings for routinizations, it should be tested, how well the effects reviewed by Betsch et al. (2002) are explained by these models. These effects are: (1) Identification of the decision situation causes activation of the routine. This effect can be explained by the context model, but not by the instance theory of automaticity. In the context model, both relevant information as well as a complete context is stored in memory, whereas for the instance theory of automaticity only the relevant information is encoded, as encoding requires attention in this theory. (2) Recognition of a decision situation can cause selection of the routinized option. Since both models rely on recognition based retrieval of instances from memory, this effect can be explained by both theories. (3) The stronger the routine, the more likely the routinized option is chosen. This effect is better explained by the instance theory of automaticity, as this theory proposes a dual route. The more instances are available for retrieval, the less likely the complicated algorithm is chosen instead. On the other hand, for the context model, there is only probabilistic retrieval, so the probability of choosing the routine behavior is only dependent on the number of routine conforming memory traces vs. number of non-conforming memory traces. This ratio may be dependent on routine strength, but can also be influenced by other factors. (4) The depth of the information search is decreased with stronger routines. Again this is well explained by the instance theory of automaticity. Applying this theory to decisions would mean that information search is part of the algorithm, which runs simultaneously to memory retrieval. Since this algorithm has less time to run before being stopped due to a retrieved instance, this would explain the decreased information search. (5) Stronger routines cause less elaborate information searches. This effect can be explained by a similar reasoning to the one above for the instance theory of automaticity, but not for the context model. (9) The influence of routines on the behavior is mostly independent from intentions. This effect is well explained by the instance theory of automaticity, as for this theory, retrieval is obligatory and cannot be

stopped. (10) The stronger the routine, the less intentions can cause a routine deviation. Again this could be explained by the instance theory of automaticity, at least assuming that intentions are only able to influence algorithmic processing, but not the retrieved instances. Hence, the stronger the routines, the more likely an instance is retrieved instead of using the algorithm, so that the routinized decision is chosen. The other effects cannot be explained well by either of the given models. In neither model, there is any clear indication, on which kind of information is considered, so that it cannot be explained why more confirmatory information should be searched (6), or why contradictory information should have less influence with stronger routines (7). Additionally, it is not clear, why time pressure should have an influence. Finally perceived novelty neither plays a role for the theory of automatization, nor for the context model, so that no influence would be predicted. This comparison shows that a great deal of effects can be explained by the instance theory of automaticity, further indicating that event files may be a part of decision making processes.

Finally, I will test, if an exploration/exploitation trade-off can be predicted by the theory of automatization and event files. The instance theory of automaticity assumes that when a problem is encountered both an algorithm is started, which may solve the problem, as well as a probabilistic retrieval of a previous instance. In case the algorithm is run, this may lead to a different solution, at least in probabilistic situations, or in situations of uncertainty. Given the situation above, the presented information does not indicate which of the two lotteries is better – only memory traces may give such an indication. So the only possible algorithm is, to pick any of the lottery at random – since both are indistinguishable without memory. Hence, if the algorithm wins the race against the retrieval process, in 50% the lottery is chosen, which has previously turned out to be worse (exploration). The more instances are available, the less likely the worse lottery is chosen, leading to more exploitation and less exploration with further experience. Hence, this model can be used to predict a detailed strategy in which exploration and exploitation

is balanced. Further empirical evidence is needed to test, if a similar strategy is used by human decision-makers. A further solution to the exploration/exploitation conflict is given by the intertrial relation for event files. One rational strategy to balance exploitation and exploration would be, to rely on perceived novelty. In a new environment, the probabilities for the outcomes may change, so it would be sensible, to first perform some exploration again, to learn the new probabilities. Betsch et al. (2002) review literature showing that routine deviations are more likely if the situation is new. Detecting if the environment changed requires that not only the relevant information is processed, but also irrelevant information, as a change in irrelevant information may indicate a change of the environment. Event files may also be part of such an environmental monitoring process.

4.2. Models for Perception, Action and Decision Making

This section will now compare a model for action and perception with a model for decision making, to point out further theoretical parallels between these two fields. The model for perception and action control is the HiTEC model, implemented as a computational model for the theory of event coding. The model that will be presented for decision making, is the parallel constraint satisfaction model (PCS) for intuitive decision making. Both models are based on recurrent neural networks, making them suitable for a comparison.

4.2.1. A computational model for the theory of event coding

Haazebroek, van Dantzig, and Hommel (2011) present a computational model (*HiTEC*) based on the theory of event coding. In this model perception and action planning are not done in separate steps, but are intertwined. A given task influences which features are perceived, and the perceived features determine how the task is executed. This model uses a connectionistic architecture. The units of the network correspond to codes in the theory

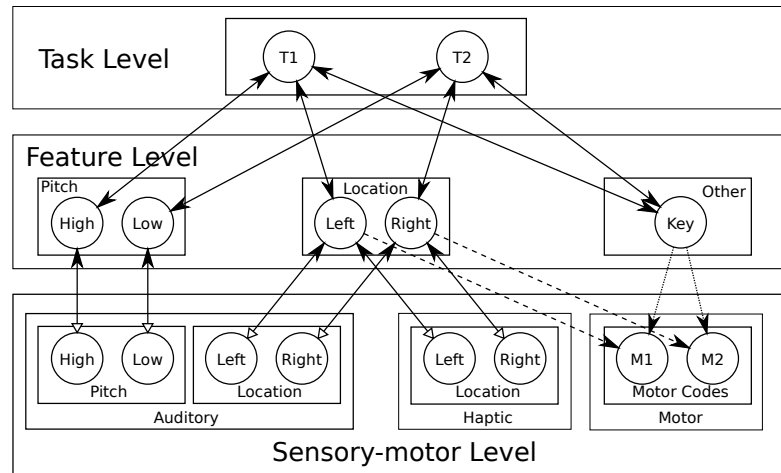


Fig. 4.1. The HiTEC model derived from the theory of event coding. The connections and units represent the codes used for an auditory Simon task. Solid lines indicate fixed weights, dotted lines are learned weights (Haazebroek, van Dantzig, & Hommel, 2011, p. 357). The *left* and *right* feature codes are connected to both the motor codes required for selecting the correct button as well as to the *auditory left* and *right* codes.

of event coding. Multiple units are organized in modules, each module representing one feature map. Units within the same module are connected by inhibitory connections. The modules are organized in three layers (see Figure 4.1). At the lowest level the proximal perception and motor codes are represented. The next level (feature Level) maps these proximal codes onto distal feature codes. At this level common coding is used to map both perception and motor codes to their common representation, e. g., the code *left* which can both indicate a response on the left side, as well as a perception on the left side. Above the feature level is the task level. In the case of the Simon task (J. R. Simon & Wolf, 1963) modeled in Figure 4.1 there are two tasks, either pressing the left key or pressing the right key. Associations between feature codes and motoric actions are learned by activating random motor codes and perceiving the resulting stimuli. For example, a baby which holds a rattle might randomly activate a motor code which represents movement of the arm, which results in a rattling sound. In this case, the motor code for

moving the arm, and the stimulus code for the rattling noise are connected, as well as all other stimuli codes which are currently activated, e. g., the ones representing the stimuli from the visual perception of the rattle. The connection between the motor code and the corresponding event is increased using a Hebbian learning rule (Hebb, 1949/2002). Action planning is performed by activating the event code corresponding to the desired result. When the result code is activated, the activation will spread to motor codes that have been previously associated with this perception.

As Hommel (2009) puts it, event files are part of a pattern completion mechanisms. Hence, this model also is mainly a model of how pattern completion can be implemented. If any part of an event file is activated, the activation automatically spreads to all other codes. At the same time, incompatible codes are inhibited driving the model towards a consistent representation. Furthermore, this activation can be influenced by weighting task-relevant dimensions higher than task-irrelevant dimensions. The task-irrelevant dimensions will then still be activated, just not as strongly.

Event files in this model are represented by adding additional nodes, which are connected to all feature codes, which are bound within the event file (Haazebroek & Hommel, 2009b). The event files themselves are connected by inhibitory connections, so that they compete with each other for activation. The version of the model presented by Haazebroek et al. (2011, see also Figure 4.1) does not include any representations of event files. In this version the nodes at the task level serve the same purpose as the event files used in previous versions (e. g., Haazebroek & Hommel, 2009b). Hence, in this model, event files mainly serve as representation of task associations, i. e., associations between stimuli and the corresponding responses. However, event files are not part of any learning mechanism in this model. Although event files can be created by verbal instructions (Haazebroek & Hommel, 2009a), it clearly is necessary to translate the event files into permanent structures for learning. For example, in the implementation of the driving task (Haazebroek & Hommel, 2009a, see also Section 2.3) it is not clear how the event file representing the

instruction to stop at a red light will be permanently stored, so that it lasts after the event file has decayed.

4.2.2. Consistency Maximization Strategy (CMS) and Parallel Constraint Satisfaction Model (PCS)

Glöckner, Betsch, and Schindler (2008, see also Glöckner, 2010) present an approach to decision making, based on automatic processes. According to this approach, decisions are not done serially by summing up cues or by searching through cues for one that discriminates. Instead, all cues are simultaneously and automatically integrated (Glöckner, 2010). Furthermore, decisions are not assumed to be computed unidirectionally from cue to estimation of the criterion, but rather bidirectionally, i. e., the decision process itself can also influence the subjective validities of the cues (Glöckner et al., 2008). Hence, decision making is driven by Gestalt processes (e. g., Glöckner & Betsch, 2012; Glöckner et al., 2008), which try to maximize the consistency for all cues and between presented cues and the options (Glöckner et al., 2008). The option, which can be used to maximize the consistency, is the one that is chosen. The reasoning behind this assumption is that decision making is based on automatic connectionist processes of perception (Glöckner, 2010; see also Read, Vanman, & Miller, 1997). In order to maximize the consistency of the presented situation, it is necessary to reach a dominance structuring, in which one option clearly dominates the other (Glöckner, 2010). The consistent representation are similar to the Gestalten analyzed by the Gestaltists (Glöckner & Betsch, 2012).

The *consistency maximization strategy* can be modeled by the *parallel constraint satisfaction model* (PCS) shown in Figure 4.2. In this network cues and options are represented by nodes connected by bidirectional links. The weights for the links between cues and options are positive (activating) if a cue indicates a positive prediction towards an option and negative (inhibitory) if the cue negatively predicts an option. For example, if the model has to judge which city is larger, Wiesbaden or Freiburg, and is given the

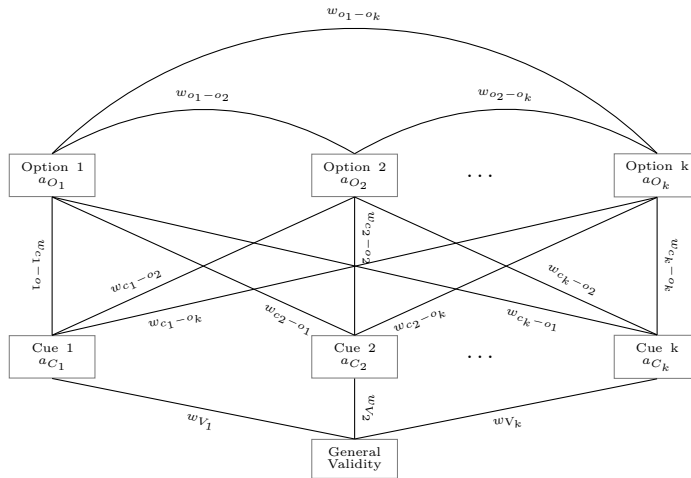


Fig. 4.2. Parallel constraint satisfaction network for probabilistic inferences. Boxes represent nodes, lines represent bidirectional links. The cues are activated through the general validity node and spread activation to the options. The options inhibit each other, to force a single choice (Glöckner, 2010, p. 313)

cue “State Capital”, then there would be a positive link between Wiesbaden and the cue, as Wiesbaden is the capital of Hesse, but negative link between Freiburg and the cue, as Freiburg is not the capital of Baden-Württemberg. The weights between the general validity node and the cues represent the initial subjective validity of the cues. The stronger a cue predicts an option, the higher the weight for the corresponding link. The options are linked strongly inhibitory, to force competition between them (Glöckner & Betsch, 2008). There are three steps that are performed to reach a decision using CMS. First, the presented information as well as associated information from memory is activated, which means the corresponding nodes and links are created. Then activation is spread from the general validity node, which has a constant activation of +1. Then activation is spread bidirectionally along the links, which reduces inconsistencies and forces a consistent representation. In the final state of the network one of the option clearly dominates over all others, due to the mutual inhibition between the options (Glöckner, 2010). The final activations of the cue nodes represent the subjective validities of the cues

after the decision process. After the decision is done, the validities are changed towards greater consistency, i. e., the subjective validity of cues which predict an option other than the chosen one are reduced in activation, whereas validities of cues which predict the chosen option are increased (Glöckner et al., 2008). Furthermore, deliberate processes may alter the network either during activation or during consistency maximization phase, e. g., to focus on specific information (Glöckner, 2010; see also Betsch, 2005). The changes in the network require cognitive control to last and are transient (Betsch, 2005). Changes can both be done by adding nodes as well as by adapting weights.

One striking property of this model is that it can predict the changes in subjective cue validities, which have been found empirically (e. g., Glöckner et al., 2008; D. Simon, Krawczyk, Bleicher, & Holyoak, 2008). For example, Glöckner et al. (2008) presented participants with a set of cues, one of which indicated a different option than the others. Participants were asked to rate the subjective validity of each cue before and after performing the decision. The subjective validity of the cue, which was not in line with the other was significantly reduced after the decision was performed, whereas the subjective validity of all other cues was increased (Glöckner et al., 2008). Since all links in PCS are bidirectional, activation can spread back from the chosen option to activate all cues which indicate that option or to inhibit all cues that indicate another option. The final activation of each cue represents the subjective validity of that cue (Glöckner et al., 2008).

4.2.3. Comparison of the Models

Both the model for the theory of event coding as well as PCS are based on the *parallel distributed processing framework* (PDP) (Rumelhart, Hinton, & McClelland, 1986; see also Haazebroek & Hommel, 2009b; Jekel, Glöckner, & Bröder, in preparation). Hence, both models are derived from an implementation of Gestalt processes (Read et al., 1997). The operation of the model, however, is described differently by the different authors.

Glöckner and Betsch (2012) points out that the PCS model is based on maximization of consistency, whereas Hommel (2009) points out that event files are part of a pattern completion mechanism. Pattern completion can also be seen as a process, which is aimed at maximizing consistency as well, by filling in missing pieces. Therefore, both models essentially perform the same task, which is inference of consistent Gestalts based on consistency-maximization.

Still, although both models are based on the same theoretical underpinning, there are some differences. For HiTEC the perceived features are activated directly, whereas for PCS activation comes from a common general validity node. Also for HiTEC the final result is that a motor response code is activated, which then causes the response to be performed. For PCS, on the other hand, the option is activated and it is not specified, how the choice is executed (e. g., by pressing a button). Then for HiTEC, there is no notion of cue validity. Although the model is able to learn using a Hebbian updating rule, the presented examples and simulations are based on situations with a fixed certain mapping between stimuli and responses (Haazebroek & Hommel, 2009b; Haazebroek et al., 2011). It is not clear from the literature how the model would perform given a task under uncertainty.

Most important for the research presented in this thesis, is the question how bindings are performed in each model. In HiTEC bindings are created by additional event file or task nodes, which link responses and perceptions. For PCS there is no clear indication given how binding works, as the concept of bindings is not well known among researchers of decision making. Still, it is possible to identify bindings in this model. First, when a decision situation is presented, positive links between the cues and the options they indicate are created. However, not only the cues that indicate an option are linked to the options, but also cues that negatively predict an option, e. g., the cue that Freiburg is not a state capital. These cues are linked with negative weights. Hence, if one interprets the links as bindings, this model is able to bound both the presence as well as the absence of a

4. Links Between Perception and Decision Making

cue. HiTEC on the other hand is only able to bind the presence of a feature, whereas the absence would require additional changes. Further, experiments on distractor-response binding should test, if the absence of features can be bound in a similar way as the presence of features. However, interpreting the links as bindings is not the only possibility. In PCS the option nodes are structurally equivalent to the event file or task nodes. In HiTEC, the task or event file nodes are the main driving factors for responses. These nodes are competing with each other, so that finally one of them dominates the others, and a response is carried out. Similarly, the option nodes are competing with each other, until one dominates the others and an option is chosen. Also option nodes accumulate the activations from all incoming codes, in a similar way like the event file nodes accumulate activations from all sensory-motor nodes. Under this interpretation, event files would not only be a part of the decision making process. Rather, the pattern completion mechanism, of which event files are a part, would be the driving mechanism, which allows us to make decisions.

Of course, one should be careful to derive conclusions by the structural similarity of these two models alone. Any interpretation should be backed up by experimental evidence. A first step is still to provide experimental evidence, for the common underlying structure shared by processes of decision making with processes of perception and action. In order to provide this evidence, I will now test, if event files, or more precisely distractor-response binding effects play a role in decision making under certainty and uncertainty. Hence, the following chapter will present the hypothesis put forth in this thesis.

5. Objective of my Thesis

Distractor-response binding has only been considered in the realm of perception and action control until now. Nevertheless, there are some effects known which show that irrelevant information can influence people's behavior not only in the area of perception and action but also in the area of judgment and decision making (Huber et al., 1982; Nisbett et al., 1981; Platzer & Bröder, 2012; Tversky & Kahneman, 1974, 1981). Moreover, there are many important parallels between both fields. Especially, both perception/action as well as decision making allow for routinization by learning. While the concrete mechanisms for routine building are still under investigation, the current theories indicate that event files may play a major role (Giesen, 2014; Hommel, 1998; Moeller & Frings, 2014c). Therefore, I investigated the hypothesis that distractor-response binding is also present in decision making under certainty as well as under uncertainty. I claim that relevant and irrelevant cues and their associated decision can become part of an event file and thereby will be automatically retrieved when any feature of this event file is encountered again — even if the repeated aspect was irrelevant for the decision situation (or rather, if the relevance cannot be reliably determined, see Section 4.1.1). By the retrieval of the saved event file, a following decision situation will be influenced. Depending on whether the current decision is the same one as in the previous decision situation, the retrieval of the event file and therefore the associated decision will facilitate the response. However, when the new decision situation indicates a different option than in the decision situation before, the retrieved decision interferes with the new decision and therefore decision making is

5. Objective of my Thesis

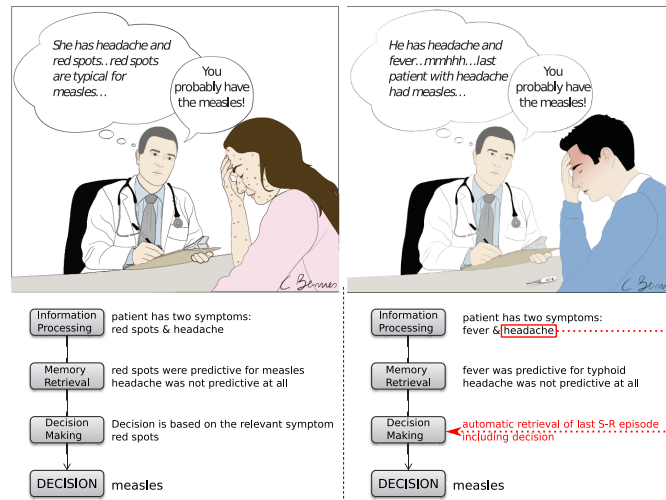


Fig. 5.1. Basic idea of how SR binding might affect decisions under uncertainty. In the diagnosis-scenario used in our experiments, the participants had to diagnose a disease of an imagined patient given two symptoms. The main hypothesis in all experiments was that an irrelevant symptom will retrieve the last encounter in which it was presented including the decision – thereby directly influencing the current decision.

hampered. I assume that this described pattern will generally occur in the reaction times (RT) and/or in the numbers of incorrect decisions¹.

To validate this hypothesis, my first step was to test if SR binding triggered by irrelevant information also occurs in deterministic decision tasks. The difference to the classification tasks used so far (e. g., Frings & Rothermund, 2011; Frings et al., 2007) is that the paradigm employed here used more complex stimulus material. While previous studies used a direct mapping between stimuli and keys or other types of responses, the mapping used here required a learned inference, which had to be performed or routinized to decide for the correct option. In previous studies participants had to classify the category of a word (Giesen & Rothermund, 2011) or if an object is smaller or bigger than a shoe box (e. g., Dobbins et al., 2004). These types of decision could easily be performed

¹depending on the speed-accuracy trade-off.

by retrieval of previously learned day-to-day knowledge. The decisions used here on, however, required knowledge learned during a training phase of the experiment, to exclude influence of day-to-day knowledge and focus the research on the decision process itself, as it is common in research on decision making. Hence, participants had to determine whether a patient has a certain disease or not (Chapter 6) or which of two diseases the patient actually has (Chapter 7 and Chapter 8; see Figure 5.1). This diagnosis paradigm adapted the distractor-to-distractor priming paradigm by Frings et al. (2007) to a decision situation. In the first series of experiments it was adapted as a decision task under certainty (experiments 1a to 1c) and later to a decision task with uncertainty (experiments 2a to 3d).

These nine experiments² are divided into three blocks. In the first section there are three experiments where the hypothesis that distractor-response binding affects decision making was tested for deterministic decision situations, i. e., the assignment between particular relevant cues and the decision was unambiguous. Hence, the given decision could be classified as either correct or false. The correct decision in each trial was indicated by the relevant cue. The irrelevant cue did not provide any valid information for the decision making process because it neither correlated with any option nor any (relevant) cue. Experiment 1a was the pilot study for this paradigm. Experiment 1b was conducted to replicate the findings of Experiment 1a with a slightly improved design. In Experiment 1c I examined if the bypass rule could serve as an alternative explanation for the results of Experiment 1a and Experiment 1b.

For the second block of experiments, the newly developed paradigm was changed slightly. The deterministic decision situation was transferred to a probabilistic one. The hypothesis was that distractor-response binding would influence decisions under uncertainty similarly

²Please note that experiment 1b, 2a, 2b, 3a are also described in an article currently submitted to the *Journal of Experimental Psychology: Learning, Memory, and Cognition* (Nett, Bröder, & Frings, submitted).

5. Objective of my Thesis

to decisions under certainty and classification tasks. In adapting the paradigm, the choice of the more probable of two options (based on Bayesian inference; Spiegelhalter & Rice, 2009) was coded as the correct decision. The probability of an option to be the correct one was indicated by the relevant cue. Again the irrelevant cues did not give any hint for any option because they neither correlated with the correct options nor any of the relevant cues. In Experiment 2a I investigated if distractor-response binding plays a role in decision making under uncertainty. Also, changing the paradigm from a decision task under certainty to a decision task under uncertainty introduced the concept of the cue validity. To test the influence of the validity simultaneously to the main hypothesis the relevant cue had either a validity of $v = .60$ or $v = .80$. The validity was varied as a within-subject factor. The hypothesis concerning the validity was that a distractor-response binding effect should be present for both validity levels. Nevertheless, I expected a different strength in distractor-response binding for both validity levels. With Experiment 2b I wanted to replicate the results of Experiment 2a and to further investigate the influence of the different validities. Therefore, the two different validity categories for the relevant cue were varied as a between-subject factor in Experiment 2b. Again I expected a significant distractor-response binding effect for both validities, but a difference in the strength of the effect.

In the third and last block, I conducted four experiments designed similar to Experiment 2a and Experiment 2b to investigate possible constraints for distractor-response binding in decision making under uncertainty and to further investigate the underlying mechanism. The first hypothesis was that distractor-response binding effects for decision making would be modulated by similar factor as distractor-response binding for classification tasks. Hence, in Experiment 3a the irrelevant cue was semantically unrelated to the decision task (i.e., the diagnosis of the disease). Research on SR binding suggests that in such a situation, integration of irrelevant information is less likely (Frings & Rothermund, 2011; Giesen & Rothermund, 2011; Hommel, 2005). Since the theory indicates that event

file mechanisms are part of the routinization processes, I also expected distractor-response binding effects to be influenced by similar factors as routinization in decision making. Betsch, Haberstroh, Molter, and Glöckner (2004) indicate that routine relapse errors are more likely under severe time pressure than under low time pressure. Hence, in Experiment 3b I tested if distractor-response binding still influences decision making if participants have no time pressure for their decisions. I assumed that distractor-response binding is an automatic process (Hommel, 2005; Hommel & Colzato, 2004, 2009) and hence participants cannot completely suppress this influence. Still, without time pressure, suppression of routine relapses becomes more likely, so I hypothesized that incorrect decisions due to event file retrieval will become less likely as well. In Experiment 3c I investigated if the representation of the actual decision or the key press used to indicate the choice is integrated in the event file. Horner and Henson (2009) indicate that multiple response representations, e. g., classifications, decisions and actions are bound simultaneously (see Section 2.3.1). The previous experiments did not allow me to distinguish if the decision or the action, i. e., the left or right keypress was bound to the cues. In the previous experiments the decision and the key press were always the same. To disentangle this confound I presented on-screen labels during the task which indicated which key was associated with which decision. For reasons of simplicity the keys were *c* and *m* as in the previous experiments, but they had no fixed association to the disease like before. Thus, there were trials in which the association between key and disease switched between prime and probe. The hypothesis was that there would also be a significant distractor-response binding effect, if the key association changed between prime and probe. In Experiment 3d I investigated if not only the decision but also the confidence in the decision can be bound in an event file. The hypothesis was that SR binding also effects the confidence in a decision similarly to the reaction times or the error rates.

All these experiments together are planned to provide further evidence of a common underlying mechanism for perception/action and decision making. Especially if Experi-

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ment 3a and Experiment 3b should indicate that distractor-response binding for decision making is both influenced by factors which influence distractor-response binding for classification tasks as well as by factors influencing relapse errors in decision making, this would provide a strong hint that both processes share a common basis.

Part II.

Empirical Evidence

6. Deterministic Decisions

To test if distractor-response binding also plays a role in more deliberate processes than simple motoric actions, I adapted the distractor-to-distractor priming paradigm (Frings et al., 2007) from a letter classification task into a decision making classification task. The setting of the decision situations was a diagnosis scene in all my experiments (similar to the scene depicted in Figure 5.1 on page 74).

Experiment 1a aimed to find distractor-response binding in a decision classification task. Thus, participants had to diagnose if a patient had the disease in question or not. The patient always named two symptoms, however, the participants knew that only one cue was useful for their decision. I designed Experiment 1a as a pilot study, and Experiment 1b to replicate the findings. The paradigm was similar with some minor refinements. In Experiment 1c I tested if the findings of the previous experiments, were caused by distractor-response binding or the bypass rule (e. g., Krueger & Shapiro, 1981). Therefore, I added two further decision displays with the same setting but different stimuli to each trial in addition to prime display and probe display.

6.1. Experiment 1a

Experiment 1a investigated distractor-response binding in deterministic decision making processes. Hence, I tested whether people decide faster and/or make more correct decisions when the previous decision has to be repeated in the following decision display and a presented irrelevant cue is also repeated than if the irrelevant cue is changed. Furthermore,

6. Deterministic Decisions

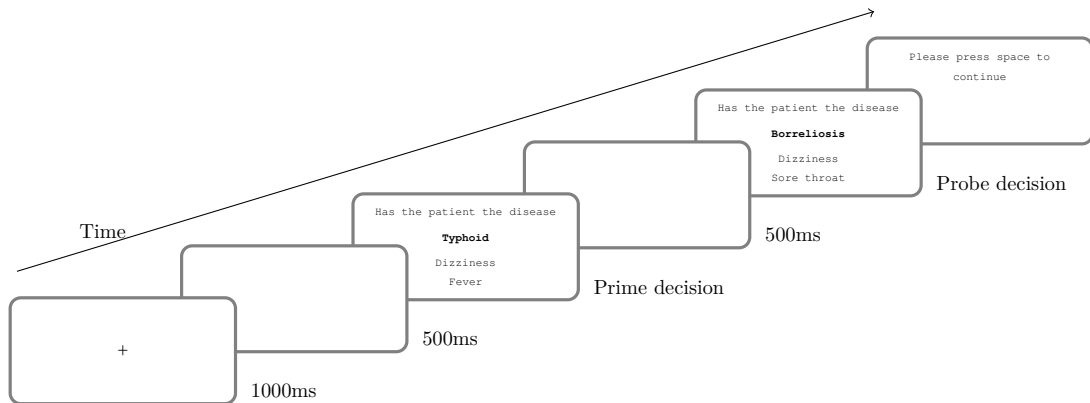


Fig. 6.1. The sequence of events of one trial in Experiment 1a. Stimuli are not drawn to scale.

I tested if people decide faster if they have to change their decision from the previous decision display to the next, if the irrelevant cue also changed, than if it was repeated.

The experimental task for the participants was to diagnose if a patient had a disease or not given two symptoms (i.e. cues) one of which was (positively) correlated (the relevant cue) with one of the three diseases whereas the other (the irrelevant cue) did not correlate with any disease or any (relevant) symptom, i.e. was not predictive.

6.1.1. Methods

Participants. Nineteen students (12 females) from the University of Trier participated in Experiment 1a. They received partial course credit for their participation. The median age of all participants was 23 (ranging from 19 to 41 years). All participants had normal or corrected-to-normal vision. The data of four participants were excluded because their prime error rate of over 15% was an outlier with respect to the error rate distribution of the whole sample (Tukey, 1977).

Materials. In the instructions, participants were asked to imagine being a doctor who is visited by couples. The two members of the couple constituted prime and probe of the sequential priming paradigm. The doctor had to diagnose the each member of the couple shortly after one another. Each member of the couple would ask if he/she had a

certain disease or not, i.e. the participants only had to decide about the presence/absence of a single disease, but no distinction between multiple diseases had to be performed. Each member of the same couple asked about the presence of the same disease. Further, each member of each couple also named exactly two symptoms that he/she had observed lately. The possible diseases were Typhoid, Borreliosis or Diphtheria. The symptoms could be grouped into relevant cues and irrelevant cues. Each relevant cue was associated to one disease, i.e., if the symptom was present the patient did have the disease, and if it was absent the patient did not. The irrelevant cues neither indicated any presence nor absence of any disease, and could be ignored. In half of the prime/probe presentations where the irrelevant cue was present the patient had the disease in question and in half of the slides the patient did not. If the disease that was asked and the symptom matched the participants had to answer *yes* and if they did not match, they had to answer *no*. In the rest of this thesis I will call relevant symptoms associated with a certain disease *valid* cues and any other symptoms *invalid* cues. The symptom indicating Typhoid was fever, for Borreliosis it was reddened skin, and for Diphtheria it was sore throat. Hence, fever, reddened skin, and sore throat were relevant cues. Sneezing, shortness of breath, and dizziness were the irrelevant cues. The participants were instructed to ignore these irrelevant cues and to base their decision only on the relevant ones.

For each decision participants were presented the question “Does the patient have the disease?” in German, at the top of the screen. Below this, the name of one of the diseases was shown and two symptoms, one relevant cue which could be valid or invalid and one irrelevant cue. The irrelevant cue was always shown above the relevant cue. The relevant cue and the irrelevant cue always changed from prime to probe. However, the disease in question remained the same from prime to probe. The participants had to press the key *c* to indicate that the patient did not have the disease at question and the key *m* that they had.

6. Deterministic Decisions

Before the main experiment participants had to perform a short practice run. Both the practice trials as well as the main experiment consisted of a prime-probe design. A trial consisted of a fixation marker (1000ms), followed by a short blank slide (500ms), followed by a prime display until the decision was made, followed by a blank white screen (500ms), followed by a probe slide until the decision was given, and followed by a slide on which the participants were asked to press the space key to continue with the next trial (see Figure 6.1). During the practice trials, participants received feedback when they made a mistake. But they received no feedback of their accuracy in the experimental trials. Furthermore, participants were reminded to decide faster when they took longer than 1500ms for a decision. This was done both in the practice trials as well as in the experimental trials. Experiment 1a consisted of 10 practice trials which were randomly selected from the trial list of the main experiment. The main part consisted of 243 experimental trials. The different stimuli were presented in a randomized order. All combinations of diseases and symptoms were equally likely throughout the whole main part of the experiment.

The experiment was programmed and run with e-Prime 2.0 Professional. The stimuli were presented in black on an Eizo 19" TFT screen on white background. All text was presented in point size 18 and in bold *Courier New* font. Data collection and stimuli presentation were done using a computer with a 3.53GHz two core CPU and 1.95GB of RAM. Stimuli were presented on a monitor at a resolution of 1280×1024 in 32 bit colors and a refresh rate of 63.9kHz horizontal and 59.9kHz vertical. A standard German QWERTZ keyboard was placed on a table between the participant and the monitor. Participants were tested individually in a soundproof chamber in sessions lasting approximately 30 min. The distance to the screen was approximately 60 cm for all participants.

Design. The design comprised three within-subject factors, namely *relevant cue relation* (relevant cue repeated=RCR vs. relevant cue changed=RCC), *irrelevant cue relation* (irrelevant cue repeated=IRCR vs. irrelevant cue changed=IRCC), and *decision*

Tab. 6.1. Reaction times and error rates for Experiment 1a

	Decision Relation			
	Decision repetition		Decision change ^a	
Reaction times (ms)				
IRC repetition	602	(99)	621	(113)
IRC change	637	(119)	627	(125C)
PE	-35	(34)	-5	(50)
Error rates (%)				
IRC repetition	3	(3)	6	(6)
IRC change	2	(2)	4	(4)
PE	1	(3)	2	(5)

^a Data for all decision change trials was averaged over target change and target repeated trials.

relation (decision repeated=DR vs. decision changed=DC). In this experiment the indicated decision changed required that relevant cue also changed, since it was fully determined by the relevant cue.

6.1.2. Results

Only trials with correct answers to the prime of the experimental phase were considered. For all possible combinations of relevant cue relation, irrelevant cue relation, and decision relation the distribution of the reaction times (RTs) was calculated. RTs that were more than 1.5 interquartile ranges above the third quartile of each RTs distribution of the whole sample were excluded from the following analyses, i.e. RTs outside of the inner fences were discarded (Tukey, 1977). Therefore, 23% of all RTs were discarded (first 18% were discarded because of errors, then 6% percent of the remaining trials were discarded because the RTs were outside of the fences). For the analysis of error rates only trials with correct answers to the prime presentation were considered, i.e. 18% of all trials were discarded. Mean RTs and error rates are depicted in Table 6.1. Separate analyses for RTs

6. Deterministic Decisions

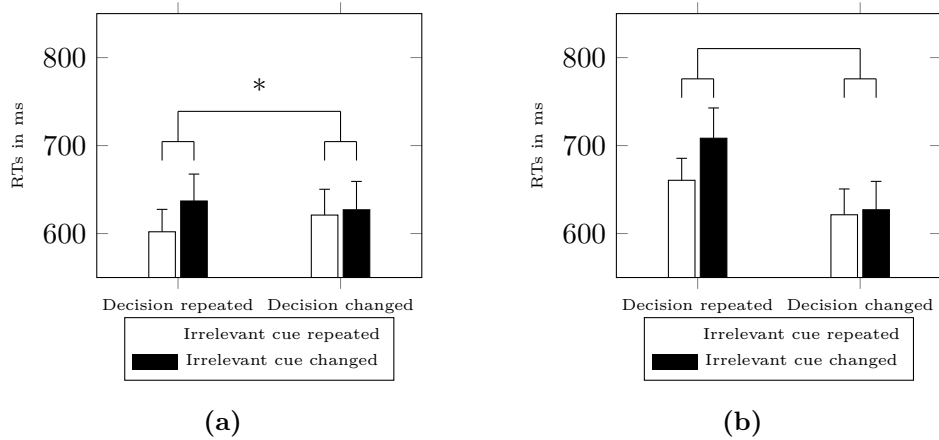


Fig. 6.2. Interaction of the irrelevant cue and the decision in the RTs for Experiment 1a. For (a) relevant cue repetition and relevant cue change trials were averaged in the analysis. For (b) only trials in which the relevant cue changed were analyzed.

and the error rates were computed. Pillai's trace was taken as a criterion for all variance analyses of repeated measurements.

A 2×2 repeated measurement analysis of variance with the within-subject factors *irrelevant cue relation* (repeated versus changed) and *decision relation* (repeated versus changed) was computed for the RTs to test if the decision behavior was modulated by the irrelevant cue. The main effect of *irrelevant cue relation* was significant, $F_{(1;14)} = 5.70, p = .03, \eta_p^2 = .29$, showing that participants were generally faster if the irrelevant cue was repeated from prime to probe ($M = 612\text{ms}, SD = 99\text{ms}$) than if the irrelevant cue changed ($M = 632\text{ms}, SD = 120\text{ms}$). However, no main effect of *decision relation* was revealed, $F_{(1;14)} = .25, p = .62, \eta_p^2 = .02$. As predicted the crucial interaction of *irrelevant cue relation* and *decision relation* was significant, $F_{(1;14)} = 4.44, p = .05, \eta_p^2 = .24$, showing that the participants were faster to answer with the same decision in the probe as in the prime when the irrelevant cue was also repeated ($M = 602\text{ms}, SD = 99\text{ms}$) than if the irrelevant cue was changed ($M = 637\text{ms}, SD = 119\text{ms}$), $t(14) = 4.02, p < .01$. However, for trials where the decision had to be changed the opposite pattern as expected occurred. I. e., the

participants decided slower when they had to change their decision from prime to probe and the irrelevant cue was also changed ($M = 627\text{ms}$, $SD = 125\text{ms}$) than if the irrelevant cue was repeated but they had to change their decision ($M = 621\text{ms}$, $SD = 113\text{ms}$). The difference was not significant $t(14) = .44$, $p = .67$ (see Figure 6.2a).

The set of trials in which the decision changed included both those where the relevant cue changed as well as those where it remained the same. To test the effect of this possible confound, I computed a second 2×2 repeated measurement analysis of variance with the within-subject factors *irrelevant cue relation* (repeated versus changed) and *decision relation* (repeated versus changed) for the RTs restricted to those trials where the relevant cue changed from prime to probe. Again a significant main effect of the *irrelevant cue relation* was revealed, $F_{(1;14)} = 35.41$, $p < .01$, $\eta_p^2 = .72$, showing that participants were generally faster if the irrelevant cue was repeated from prime to probe ($M = 640\text{ms}$, $SD = 101\text{ms}$) than if the irrelevant cue changed ($M = 668\text{ms}$, $SD = 127\text{ms}$). Furthermore, the main effect of the *decision relation* was significant, $F_{(1;14)} = 6.42$, $p = .02$, $\eta_p^2 = .31$, indicating that the participants were significantly faster when they had to change their decision from prime to probe ($M = 624\text{ms}$, $SD = 117\text{ms}$) than if they had to repeat their decision ($M = 684\text{ms}$, $SD = 112\text{ms}$). However, the interaction between *irrelevant cue relation* and *decision relation* was not significant anymore, $F_{(1;14)} = 3.85$, $p = .07$, $\eta_p^2 = .22$ (see Figure 6.2b).

For the sake of completeness I also analyzed the influence of the irrelevant cue in the trials where the relevant cue was repeated. I computed a paired t-test of the trials where the irrelevant cue changed versus those where it was repeated exclusively on the trials where the relevant cue was repeated from prime to probe. As the decision change depended on a change of the relevant cue, in these trials the decision also had to be repeated. The RTs differed significantly between the irrelevant cue repetition trials ($M = 543\text{ms}$, $SD = 105\text{ms}$) and irrelevant cue change trials ($M = 566\text{ms}$, $SD = 109\text{ms}$), $t(14) = 2.76$, $p = .02$.

Furthermore, I analyzed the relative error rates in percent the same way as the RTs. Therefore, a 2×2 repeated measurement analysis of variance with the within-subject factors *irrelevant cue relation* (repeated versus changed) and *decision relation* (repeated versus changed) was computed for the error rates. However, only the main effect of *decision relation* was significant, $F_{(1;14)} = 5.62, p = .03, \eta_p^2 = .29$, showing that participants decided less correct when they had to repeat their decision ($M = 2.5\%, SD = 1.8\%$) than if they had to change their decision ($M = 4.8\%, SD = 4.1\%$). Because of the missing significant interaction between *irrelevant cue relation* and *decision relation* in this analysis, no further analysis was computed.

6.1.3. Discussion

In Experiment 1a I analyzed if distractor-response binding occurs in deterministic decision making. The analysis of the interaction between irrelevant cue relation and decision relation clearly showed the influence of the irrelevant cue on decision making for trials with relevant cue repetition and trials with relevant cue change. Therefore, distractor-based retrieval of SR binding seems to be present in deterministic decision making. The participants needed longer to decide when the irrelevant cue was repeated from prime to probe and the decision had to be changed than if the irrelevant cue was repeated and they had to give the same decision in the prime as in the probe. Furthermore, the RTs were larger when the irrelevant cue changed from prime to probe, but the decision had to be the same than if the decision had also to be changed. Therefore, repeating the irrelevant cue adds something to the effect of mere relevant cue repetition. This interaction was significant in the RTs, but not in the error rates.

However, the repetition of the relevant cue and decision repetition were confounded. Thus, when the relevant cue remained from prime to probe, the decision had to be repeated. Furthermore, since the cue positions were fixed, in trials where both the relevant as well as the irrelevant cue were repeated, exactly the same display was presented in prime and

probe. In the other conditions the display changed always at least slightly from prime to probe. Thus, the repetition effect of relevant cue and irrelevant cue could also be explained by visual identity. Furthermore, Giesen and Rothermund (2014) showed that distractors are not only bound to responses but also to the target. Hence, RTs can be influenced by the interaction of distractor and target relation in addition to distractor and response relation. Therefore, I computed two additional analyses – one exclusively for trials with relevant cue change and one for relevant cue repetition. In these analyses the confound was eliminated. However, the interaction between *irrelevant cue relation* and *decision relation* was no longer significant. The reason remains unclear. Two interpretations are possible: on the one hand, the interaction could be caused by the confound and not by distractor-response binding. But on the other hand, because the trials with relevant cue repetition were deleted in this analysis, fewer trials could be analyzed which results in a weaker statistical power to detect an effect. Frings et al. (2007, Experiment 1b) ruled out the explanation of visual identity by switching the locations of the target and distractor stimuli from prime to probe. Furthermore, in Experiment 2 they disentangled the confound of target and response repetition and could show again that the distractor retrieved the response. To replicate the findings of this pilot study and to test if the interaction of irrelevant cue relation and decision relation is still significant without the confound of target repetition, I conducted Experiment 1b.

6.2. Experiment 1b

In Experiment 1b, the hypothesis that distractor-response binding plays a role in decision classification tasks was tested again. Experiment 1a had two methodical short-comings which were reduced in Experiment 1b. First, in the previous experiment the disease was always repeated from prime to probe. In Experiment 1b, the disease was also varied orthogonally to the relevant and irrelevant cue. Further, in Experiment 1a the indicated decision changed simultaneously with the relevant cue, since it was fully determined by the relevant cue. In Experiment 1b this confound was reduced, i. e., now the decision could be changed by changing either the disease or the relevant cue.

6.2.1. Methods

Participants. Further, thirty-six students (23 females) from the University of Trier participated in Experiment 1b. They received partial course credit for their participation. The median age of all participants was 21 (ranging from 18 to 26 years). All participants had normal or corrected-to-normal vision. The data of one participant was excluded because their error rate of 93% in the prime decisions was an outlier with respect to the error rate distribution of the whole sample (Tukey, 1977).

Materials. The material and procedure were the same as in Experiment 1a (see Figure 6.1 on page 82) with the following exceptions: 1) The disease could change from prime to probe. 2) Experiment 1b consisted of 10 practice (randomly chosen from the trial list of the main experiment) and 224 experimental trials. Like in the previous experiment, the stimuli were presented in a randomized order.

Design. The design comprised four within-subject factors, namely *relevant cue relation* (relevant cue repeated=RCR vs. relevant cue changed=RCC), *irrelevant cue relation* (irrelevant cue repeated=IRCR vs. irrelevant cue changed=IRCC), *disease relation* (illness repeated=IR or illness changed=IC), and *decision relation* (decision repeated=DR vs. decision changed=DC). As the decision could only be changed by also changing

Tab. 6.2. Reaction times and error rates for Experiment 1b

	Decision Relation			
	Decision repetition		Decision change	
Reaction times (ms)				
IRC repetition	926	(141)	932	(127)
IRC change	963	(150)	943	(167)
PE	-37	(58)	-11	(81)
Error rates (%)				
IRC repetition	12	(12)	21	(25)
IRC change	14	(15)	20	(21)
PE	-2	(7)	1	(12)

either the disease or the relevant cue, not all combinations of these factors were possible. This means that the disjunction of the RCC and IC was a necessary (but not sufficient) condition for DC. The factors were fully balanced, i.e. all possible combinations of factors were presented 16 times.

6.2.2. Results

Only trials with correct answers to the prime of the experimental phase were considered. For all possible combinations of relevant cue relation, irrelevant cue relation, disease and decision relation the distribution of the RTs was calculated. RTs that were more than 1.5 interquartile ranges above the third quartile of each RT distribution of the whole sample were excluded from the following analyses, i.e. RTs outside of the inner fences were discarded (Tukey, 1977). Therefore, 20% of all RTs were discarded (first 16% were discarded because of errors, then 5% percent of the remaining trials were discarded because the RTs were outside of the fences). For the analysis of error rates only trials with correct answers to the prime presentation were considered, i.e. 16% of all trials were

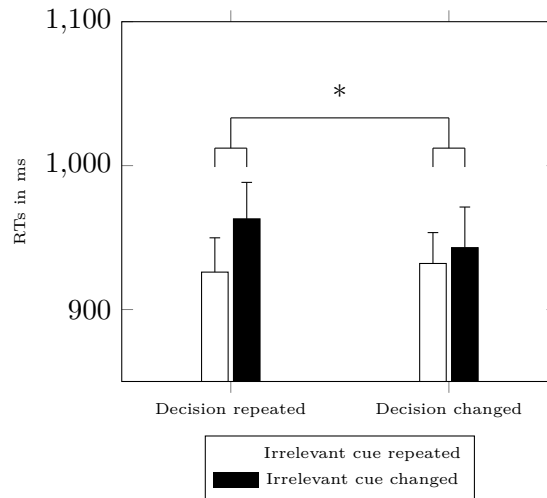


Fig. 6.3. Mean reaction times for Experiment 1b

discarded. Mean RTs and error rates are depicted in Table 6.2. Separate analyses for RTs and error rates were computed. Pillai's trace was taken as a criterion for all variance analyses of repeated measurements.

A 2×2 repeated measurement analysis of variance with the within-subject factors *irrelevant cue relation* (repeated versus changed) and *decision relation* (repeated versus changed) for the RTs was computed to test if the decision behavior could be modulated by the irrelevant cue. The main effect of *irrelevant cue relation* was significant, $F_{(1;34)} = 5.65, p = .02, \eta_p^2 = .14$ showing that participants were generally faster if the irrelevant cue was repeated from prime to probe ($M = 929\text{ms}, SD = 134\text{ms}$) than if the irrelevant cue changed ($M = 953\text{ms}, SD = 159\text{ms}$). The factor *decision relation* revealed no significant main effect, $F_{(1;34)} = 1.04, p = .32, \eta_p^2 = .03$. Most importantly, the hypothesized interaction between *irrelevant cue relation* and *decision relation* was significant, $F_{(1;34)} = 4.41, p = .04, \eta_p^2 = .12$, showing that participants needed longer for their decision when they had to change the decision from prime to probe and the irrelevant cue was repeated ($M = 932\text{ms}, SD = 127\text{ms}$) than if the irrelevant cue was changed ($M = 943\text{ms}, SD = 167\text{ms}$), $t(34) = 3.76, p < .01$. Furthermore, the participants were

faster, when they had to repeat their decision and the irrelevant cue was also repeated from prime to probe ($M = 926\text{ms}$, $SD = 141$) than if the irrelevant cue was changed, but the decision should be repeated ($M = 963\text{ms}$, $SD = 150\text{ms}$), $t(34) = .82$, $p = .42$ (see Figure 6.3).

To control if this significant interaction between *irrelevant cue relation* and *decision relation* was moderated by the relevant cue or the disease, two $2 \times 2 \times 2$ variance analyses for repeated measurements for RTs were computed, one for the within-subject factors *relevant cue relation* (repeated versus changed), *irrelevant cue relation* (repeated versus changed), and *decision relation* (repeated versus changed). However, the three-way interaction between *relevant cue relation*, *irrelevant cue relation* and *decision relation* was not significant, $F_{(1;34)} = .19$, $p = .67$, $\eta_p^2 < .01$, which shows that the *relevant cue relation* did not moderate the interaction between *irrelevant cue relation* and *decision relation*. Furthermore, the analysis of *disease relation* (repeated versus changed), *irrelevant cue relation* (repeated versus change), and *decision relation* (repeated versus changed) also did not reveal a significant three-way interaction, $F_{(1;34)} = .17$, $p = .69$, $\eta_p^2 < .01$. Therefore, the disease did not moderate the interaction between *irrelevant cue relation* and *decision relation*.

Error rates were analyzed in the same way as RTs. A 2×2 variance analysis for repeated measurements for the within-subject factors *irrelevant cue relation* (repeated versus changed) and *decision relation* (repeated versus changed) for the error rate revealed only a main effect of *decision relation*, $F_{(1;34)} = 7.86$, $p < .01$, $\eta_p^2 = .19$, showing that participants made fewer wrong decisions if they had to repeat their decision ($M = 13\%$, $SD = 14\%$) instead of changing it ($M = 21\%$, $SD = 13\%$).

6.2.3. Discussion

The results of Experiment 1b showed that distractor-response binding influences deterministic decision making. The participants needed longer to decide when the irrelevant

cue was repeated from prime to probe and the decision had to be changed than if the irrelevant cue was repeated and they had to give the same decision in the prime as in the probe. Furthermore, the RTs were larger when the irrelevant cue changed from prime to probe, but the decision had to be the same as when the decision also had to be changed. This pattern was similar to the one in Experiment 1a, i. e., there was a significant interaction in the RTs, but not in the error rates.

6.3. Experiment 1c

Experiments 1a and 1b support the idea of distractor-response binding processes in deterministic decision making situations. Thus, the irrelevant cue influenced the RTs for a decision. Nevertheless, there is another explanation for these results – namely the *bypass rule* (e. g., Fletcher & Rabbitt, 1978; Krueger & Shapiro, 1981; Smith, 1968). The bypass rule states that immediately repeated stimuli trigger the associated response. Therefore, the bypass rule would explain why the participants are faster when they have to repeat their decision when the irrelevant cue is also repeated than if the irrelevant cue is changed. However, the bypass rule has one major difference to the theory of event coding (Hommel et al., 2001, see Section 2.3): the bypass rule requires that the stimulus which causes a decision repetition appears immediately before the current decision. Hommel and Colzato (2004) however indicate that event files can last at least 4s, so that they are available even if different stimuli are presented in between. Furthermore, Frings (2011) could show that distractor-response binding decays after about 1s. Therefore, I conducted an experiment in which the probe did not immediately follow the prime but the participants had to solve another decision task between prime and probe. Thus, in Experiment 1c a trial did not only consist of a prime-probe sequence but also included two additional displays. One of these two displays was always placed between the prime and the probe to eliminate the possibility of the alternative explanation by the bypass rule.

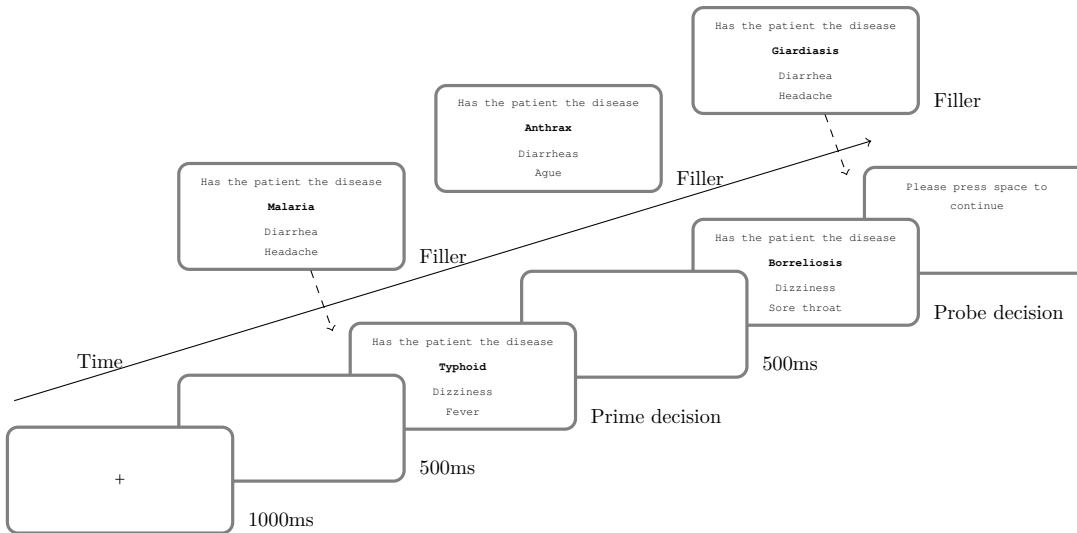


Fig. 6.4. Sequence diagram for a single trial in Experiment 1c. In contrast to the sequence in Experiment 1b several filler slides were added. One Filler always appeared between Prime and Probe, the second was either inserted before Prime or after Probe.

6.3.1. Methods

Participants. Further, thirty-nine participants (31 females) from the University of Trier participated in Experiment 1c. They received partial course credit for their participation. The median age of all participants was 21 (ranging from 18 to 51 years). All participants had normal or corrected-to-normal vision. The data of four participants were excluded because their error rates of over 29% were outliers with respect to the error rate distribution of the whole sample (Tukey, 1977).

Materials. The material and procedure were the same as in Experiment 1b with the following addition: A trial consisted not only of the fixation cross display, the blank display, the prime display, the probe display, and the question to continue display, but had also two filler displays. A filler display was designed like a probe or prime display, but instead of the diseases Typhoid, Borreliosis or Diphtheria, three other diseases were presented. The diseases which only were shown in the filler displays

were Giardiasis, Malaria, or Anthrax. The diseases on the filler displays also had a set of valid and invalid symptoms for each disease. These symptoms only appeared on the filler displays and never on the prime or probe displays. The association of diseases and the relevant symptoms in the filler displays were as followed: nausea indicated Giardiasis, headache indicated Malaria, and ague indicated Anthrax. The symptoms categorized as irrelevant symptoms were abdominal pain, diarrhea, and coughing for the filler displays. Thus, in the two filler displays the participants had the same decision classification task, only with other cues and options. As in the prime or probe display, one relevant cue and one irrelevant cue were listed on the display. The first one was always the irrelevant cue and the second one was the relevant cue. Both were fully randomized. The response keys for the filler displays were the same as for the prime and probe displays. The participant had to press the key *c* for *yes* and the key *m* for *no*. There was always at least one filler display between prime and probe. The other filler display could appear before the prime display, after the probe display or as a second filler display between prime and probe (see Figure 6.4).

Design. The design comprised six within-subject factors, namely relevant cue relation (repeated versus changed), irrelevant cue relation (repeated versus changed), disease relation (repeated versus changed), decision relation (repeated versus changed), the position of the second filler display (before prime, between prime and probe versus after probe), and the decision relation in the filler (repeated versus changed). The factors for the main prime and probe setup were fully balanced, i.e. all possible combinations of factors were presented with equal cardinality, the filler display order was also balanced, but the decision relation within the filler displays was not. situation

6.3.2. Results

Only trials with correct answers to the prime of the experimental phase were considered. For all possible combinations of relevant cue relation, irrelevant cue relation, disease

Tab. 6.3. Reaction times and error rates for Experiment 1c

	Decision Relation			
	Decision repetition		Decision change	
Reaction times (ms)				
IRC repetition	1069	(145)	1023	(106)
IRC change	970	(97)	966	(94)
PE	99	(118)	58	(72)
Error rates (%)				
IRC repetition	9	(7)	16	(14)
IRC change	7	(7)	15	(14)
PE	2	(9)	1	(12)

relation, filler relation, and decision relation the distribution of the RTs was calculated. RTs that were more than 1.5 interquartile ranges above the third quartile of each RTs distribution of the whole sample were excluded from the following analyses, i.e. RTs outside of the inner fences were discarded (Tukey, 1977). Therefore, 20% of all RTs were discarded (first 15% were discarded because of errors, then 5% percent of the remaining trials were discarded because the RTs were outside of the fences). For the analysis of error rates only trials with correct answers to the prime presentation were considered, i.e. 15% of all trials were discarded. Mean RTs and error rates are depicted in Table 6.3. Separate analyses for RTs and the error rates were computed. Furthermore, Pillai's trace was taken as a criterion for all variance analyses of repeated measurements.

An ANOVA for repeated measurements of the RTs with the within-subject factors *irrelevant cue relation* (repeated versus changed) *decision relation* (repeated versus changed) revealed two significant main effects. First, a significant main effect of *irrelevant cue relation* was found $F_{(1;34)} = 39.91, p < .01, \eta_p^2 = .54$, showing that participants were generally faster when the irrelevant cue changed ($M = 968\text{ms}, SD = 88\text{ms}$) than when it was repeated ($M = 1045\text{ms}, SD = 116\text{ms}$). Further, there was a main effect of *decision*

6. Deterministic Decisions

relation, $F_{(1;34)} = 6.06, p = .02, \eta_p^2 = .15$, showing that participants decided faster when they changed their decision ($M = 993\text{ms}, SD = 93\text{ms}$) than when they repeated it ($M = 1020\text{ms}, SD = 109\text{ms}$). However, the crucial interaction between *irrelevant cue relation* and *decision relation* was not significant, $F_{(1;34)} = 3.47, p = .07, \eta_p^2 = .09$.

To test if the RTs were influenced by the reaction given to the last slide before the probe, another analysis was computed. An ANOVA for repeated measurements of the RTs with the within-subject factors *irrelevant cue relation* (repeated versus changed), *decision relation* (repeated versus changed), and *filler relation* (repeated versus changed)¹ revealed the same main effects as the analysis above. The three-way interaction of *irrelevant cue relation*, *decision relation*, and *filler relation* also failed to reach statistical significance, $F_{(1;34)} = 1.20, p = .28, \eta_p^2 = .03$. For completeness sake, I also present the following significant results: the interaction between *irrelevant cue relation* and *filler relation* was significant, $F_{(1;34)} = 5.59, p = .02, \eta_p^2 = .14$, as well as the interaction between *decision relation* and *filler relation*, $F_{(1;34)} = 18.89, p < .01, \eta_p^2 = .36$. No further results were significant.

An ANOVA for repeated measurements for the error rates with the within subject factors *irrelevant cue relation* (repeated versus changed), *decision relation* (repeated versus changed) revealed a significant main effect of *decision relation*, $F_{(1;34)} = 19.04, p < .01, \eta_p^2 = .36$, showing that participants made more correct decisions when they repeated their decision ($M = 7.9\%, SD = 5.7\%$) than when they changed it ($M = 15.4\%, SD = 12.8\%$). However, the crucial interaction between *irrelevant cue relation* and *decision relation* was not significant, $F_{(1;34)} = .43, p = .52, \eta_p^2 = .01$. No other effects were significant.

¹Meaning that the decision between filler and probe was either the same (filler repeated) or a different one (filler changed). Remember that the decisions were like in prime probe either key press *c* for *yes* or the key press *m* for *no* but the diseases and cues were different.

Again to test for an influence of the decision in the last slide before the probe, another ANOVA with the within-subject factors *irrelevant cue relation* (repeated versus changed), *decision relation* (repeated versus changed), and *filler relation* (repeated versus changed) was computed. This analysis again revealed the same significant main effect of *decision relation*, but also a significant main effect of *filler relation*, $F_{(1;34)} = 11.80, p < .01, \eta_p^2 = .26$, showing that participants made more correct decision when they had to make a different decision in the filler and in the probe ($M = 9.2\%, SD = 7.0\%$) than when they had to make the same decision ($M = 14.0\%, SD = 11.3\%$). The three-way interaction between *irrelevant cue relation*, *decision relation*, and *filler relation* was not significant, $F_{(1;34)} = .41, p = .53, \eta_p^2 = .01$. For completeness: again the interaction between *irrelevant cue relation* and *filler relation* was significant, $F_{(1;34)} = 4.84, p = .04, \eta_p^2 = .13$.

6.3.3. Discussion

In Experiment 1c, no distractor-response binding could be found. However, it is still not clear if the interaction of irrelevant cue relation and decision relation that was revealed in the previous experiments is due to the bypass rule or distractor-response binding. Since there was no clear interaction in Experiment 1c, the bypass rule cannot be ruled out clearly, yet. Nevertheless, distractor-response binding cannot be fully ruled out as a cause either. The effect size in Experiment 1c was $\eta_p^2 = .10$ while in Experiment 1b the effect size was $\eta_p^2 = .12$. In both experiments only a small effect was found (Cohen, 1988). Furthermore, the effect was only a little smaller in Experiment 1c, and both experiments used the same number of valid data sets (taken from 35 participants). Since the p -value in the previous experiment was at .04, i. e., close at the α -value of .05, this number of participants was only just enough to detect an effect size of $\eta_p^2 = .12$. In Experiment 1c the effect was too small to be detected (O'Keefe, 2007). Moreover, since event files triggered by distractors only last about 1s (Frings, 2011), this may account for the reduced effect size.

7. Decisions under uncertainty

Since in day-to-day life, decisions are usually made under uncertainty, I examined if distractor-response binding also plays a role in decision making under uncertainty. Thus, I adapted the paradigm used in the experiments presented in Chapter 6 from a decision task under certainty to a task-set with uncertainty. Note that while some studies of SR binding refer to the presented tasks as decision tasks (e. g., Denkinger & Koutstaal, 2009; Horner & Henson, 2009, 2011), this terminology does not follow the one used in this thesis, insofar as these tasks did not require any inference. Furthermore, the adaptation of the task-setting as an uncertain decision situation is completely new. The setting was again a diagnosis scene. However, now the participant had to say which of two diseases – Typhoid or Diphtheria – a patient had.¹ Again they were presented two cues, i. e., symptoms. One cue was relevant (target) for the decision to be made, whereas the other was not (distractor). The validity of the relevant cue was either $v = .80$ or $v = .60$. The validity of the irrelevant cue was always $v = .50$. The irrelevant cue did not correlate with any of the valid cues. The participants had to know the correct validities of each cues, to be able to infer the correct choices. Previous studies have shown that the behavior of participants is different depending on whether they are simply shown the validities, or if they have accumulated experience about the cues (description-experience gap, see Hertwig & Erev, 2009). To avoid any influence of this description experience gap, participants were both

¹ In the experimental settings discussed in Chapter 6 the participants had to answer if a patient had or did not have the disease in question.

presented the conditional probabilities, and also had to perform a long practice part (in the most experiments over 100 trials). A trial in the practice part had no prime-probe sequence; but after the first decision, feedback was presented indicating if the participant made a correct or incorrect decision (see Figure 7.1). To prevent further learning of cue validities during the experimental part, no feedback was given After the first decision display (prime) no there was no feedback. Instead a second decision display (probe) followed (see e. g., Figure 7.2 on the next page). Again, there was no feedback about the decision in the probe.

Furthermore, I had to define in comparison to the experiments in Chapter 6 and the original paradigm by Frings et al. (2007) what is meant by *errors* in this newly developed paradigm. I define errors in this paradigm as the decisions that are not in line with the decision indicated by the probabilities. I name them incorrect decisions (or errors). As there was only one valid cue in all slides, the probability of the correct decision is only determined by the valid cue and no Bayesian inference (Spiegelhalter & Rice, 2009) is needed. Since I expected different numbers of incorrect decisions for cues with $v = .60$ than for cues with $v = .80$, I will compute an additional analysis for each different validity in the probe for all experiments in Chapter 7 and 8, where the main analysis indicated a significant interaction.

7.1. Experiment 2a

7.1.1. Methods

Participants. Thirty-one students (24 females) from the University of Trier participated in Experiment 2a. They received partial course credit for their participation. The median age of all participants was 21 (ranging from 19 to 33 years). All participants had normal or corrected-to-normal vision.

Tab. 7.1. Conditional probabilities of the symptoms given the diseases, symptom validities and a priori probabilities of each symptom. Only the conditional probabilities of the symptoms were presented to participants.

	Typhoid	Diphtheria	Validity	Symptom Probability
Fever	32%	11%	80%	43%
Sore throat	11%	32%	80%	43%
Dizziness	38%	32%	60%	70%
Nausea	32%	38%	60%	70%
Coughing	44%	44%	50%	88%
Headache	44%	44%	50%	88%

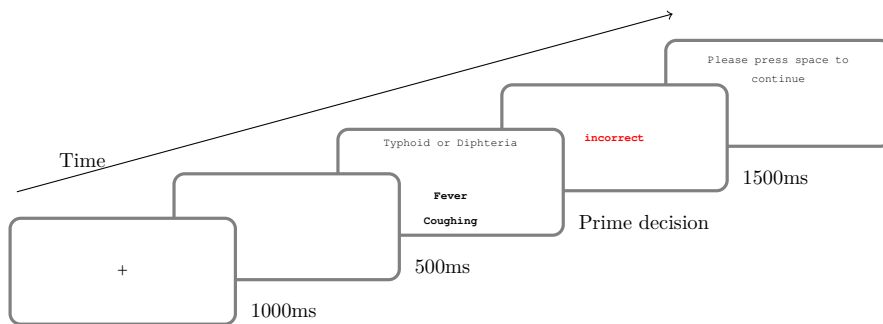


Fig. 7.1. The sequence of events during practice trials in Experiment 2a. Stimuli are not drawn to scale.

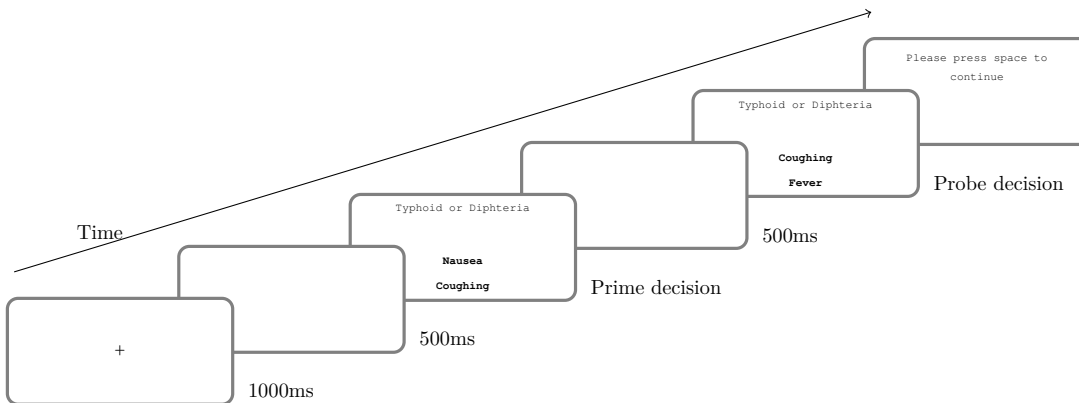


Fig. 7.2. The sequence of events of one trial in Experiment 2a. Stimuli are not drawn to scale.

7. Decisions under uncertainty

Materials. The materials and procedure were similar to the previous experiments described in Chapter 6 (see Figure 7.2).

The setting of Experiment 2a was again a diagnosis scene. The participant had to act as a doctor. They had to diagnose, if the patient had the disease Typhoid or Diphtheria. The patients reported two symptoms which they had. Using the symptoms the participant had to infer, which disease was more likely. In order to be able to distinguish between both diseases, participants were given a table with the conditional probabilities (see Typhoid and Diphtheria in Table 7.1) of all symptoms given both diseases in the instructions and on a paper sheet that was lying next to the screen during the whole experiment. This table allowed for grouping the symptoms into three classes: those symptoms with a highly associated disease, those with a moderately associated disease, and those symptoms without any association. Symptoms which were associated to a disease had a higher conditional probability given the associated disease than with the other disease. The associated symptoms had an a priori validity of $v = .80$ or $v = .60$ for one of the both diseases. The highly associated symptoms for Typhoid and Diphtheria were fever and sore throat, respectively. The moderately associated symptoms for Typhoid and Diphtheria were dizziness and nausea, respectively (see column *Validity* in Table 7.1). The non-associated symptoms had an a priori validity of $v = .50$. The non-associated symptoms were coughing and headache. As the presence of any non-associated symptom did not change the likelihood of the diseases, no inferences were possible using these symptoms, hence, they were irrelevant cues in all prime/probe presentations where they appeared. The same random assignment between symptoms and diseases was chosen for all participants. To give participants a further indication of the likelihood for each disease given two symptoms, they had to perform 132 practice trials. During the practice trials the participants were able to learn that the irrelevant cue was unrelated to the likelihood of the disease. The participants learned via feedback that was given after their decision was recorded. Through this feedback the participants

were able to learn the correct validities². The participants were also requested to decide faster if they took more than 2500ms for a decision in the practice as well as in the experimental trials.

For each prime and probe display in the 132 experimental trials participants were presented the question “Does the patient have Typhoid or Diphtheria?” in German, at the top of the screen. Below that, two symptoms were listed, one relevant cue which could be associated with $v = .80$ or $v = .60$ and one irrelevant cue. The validity of the relevant cue always changed from prime to probe. Therefore, there were trials with a relevant cue of $v = .80$ in the prime and a relevant cue of $v = .60$ in the probe and vice versa. Thus, relevant cue repetition and decision repetition were not confounded (as there never was any relevant cue repetition). The symptoms were not equally likely across all displays taken together, i.e. some symptoms were more frequent altogether and hence more likely to appear on any random display (see column *symptom probability* in Table 7.1).

The respective positions of the irrelevant and the relevant cue were randomized. The participants had to press the key *c* if they thought the patient had Typhoid or the key *m* when they thought that the patient had Diphtheria.

Experiment 2a was also programmed in e-Prime 2.0 Professional and run in the same laboratory as the previous experiments.

Design. The design comprised three within-subject factors, namely *irrelevant cue relation* (repeated versus changed), *decision relation* (repeated versus changed), and the *validity* of the relevant cue in the probe ($v = .80$ versus $v = .60$). The factors were fully balanced, i.e. all possible combinations of factors were presented 8 times. There also were 68 additional trials which did not follow the sequential priming pattern to avoid the recognition of a pattern by the participants; e. g., these trials repeated both the relevant

²Over all slides with the same cue, the proportion of slides where the associate disease was correct, was equal to v . For all irrelevant cues, both diseases were correct with equal ratio.

cue as well as the irrelevant cue. These trials were not included in the analyses. In all trials included in the later analysis, the relevant cue was always changed between prime and probe. At the same time, the validity was always changed between prime and probe. Hence, for a probe with $v = .80$ the prime would indicate a response with a likelihood of $v = .60$ and vice versa.

7.1.2. Results

I calculated and cleaned the distribution of RTs in the same way as for Experiment 1a. Therefore, 30% of all RTs were discarded (first 26% were discarded because of prime errors, then 5% of the remaining trials were discarded because the RTs were outside of the fences, see Tukey, 1977). I also analyzed the numbers of incorrect decisions in the same fashion as in Experiment 1a. For the analysis of error rates, only trials with correct decisions to the prime presentation were considered, i.e. 26% of all trials were discarded. Mean RTs and error rates are depicted in Table 7.2.

Separate analyses for RTs and number of incorrect decisions were computed. Furthermore, Pillai's trace was taken as a criterion for all variance analyses of repeated measurements.

First, I performed a $2 \times 2 \times 2$ ANOVA on the percentage of incorrect answers with the factors *irrelevant cue relation* (repeated versus changed), *decision relation* (repeated versus changed), and *validity strength* ($v = .80$ versus $v = .60$). The analysis revealed a main effect of *validity strength* $F_{(1,30)} = 13.90, p < .01, \eta_p^2 = .317$, showing that participants gave the incorrect decision in 42% of the trials with $v = .60$ ($SD = 20\%$) and in 27% ($SD = 17\%$) of the trials with $v = .80$. This main effect was most likely due to the participants matching the probabilities of the options with the ones presented during the practice trials (Gaissmaier & Schooler, 2008). Furthermore, the expected interaction between *irrelevant cue relation* and *decision relation* was significant, $F_{(1,30)} = 19.15, p < .01, \eta_p^2 = .39$, indicating that the participants made less errors if they had to change their decision

Tab. 7.2. Reaction times and error rates for Experiment 2a

	Decision Relation			
	Decision repetition		Decision change	
<i>v</i> = .60 probes				
Reaction times (ms)				
IRC repetition	867	(250)	926	(255)
IRC change	908	(308)	866	(264)
PE	-41	(222)	59	(202)
Error rates (%)				
IRC repetition	42	(33)	49	(30)
IRC change	49	(32)	30	(26)
PE	-7	(38)	19	(27)
<i>v</i> = .60 probes				
Reaction times (ms)				
IRC repetition	839	(245)	839	(264)
IRC change	841	(294)	868	(245)
PE	-2	(268)	-19	(247)
Error rates (%)				
IRC repetition	18	(21)	31	(28)
IRC change	42	(33)	18	(23)
PE	-24	(29)	13	(25)

7. Decisions under uncertainty

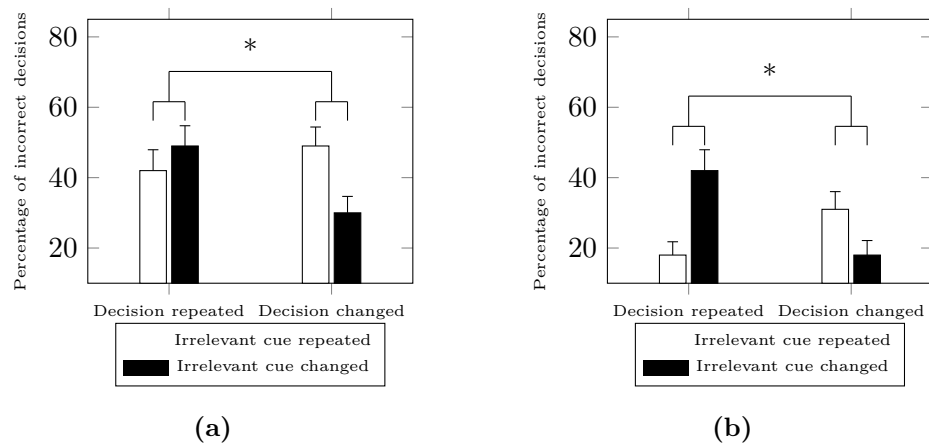


Fig. 7.3. Percentage of incorrect decisions in Experiment 2a for trials with probes with $v = 0.60$ (a) and trials with probes with $v = 0.80$ (b).

from prime to probe and the irrelevant cue also changed ($M = 23.7\%$, $SD = 19.7\%$) than if the irrelevant cue was repeated ($M = 39.7\%$, $SD = 23.8\%$), $t(30) = 4.51$, $p < .01$. If the decision had to be repeated and the irrelevant cue was also repeated, fewer incorrect decisions were made ($M = 30.1\%$, $SD = 22.6\%$) than if the decision had to be repeated and the irrelevant cue changed ($M = 45.6\%$, $SD = 26.6\%$), $t(30) = -3.20$, $p < .01$. Furthermore, a significant interaction between *validity strength* and *irrelevant cue relation* was found, $F_{(1;30)} = 6.74$, $p = .01$, $\eta_p^2 = .18$. Nevertheless, the interaction between *irrelevant cue relation* and *decision relation* was not modulated by the *validity strength* of the relevant cue, $F_{(1;30)} = 2.71$, $p = .11$, $\eta_p^2 = .08$. No further results were significant.

Because of the large difference in the number of incorrect decisions between trials with $v = .60$ and $v = .80$, two additional 2×2 ANOVAs were computed separately for the $v = .80$ and the $v = .60$ condition.

A 2×2 ANOVA with the factors *irrelevant cue relation* (repeated versus changed) and *decision relation* (repeated versus changed) exclusively on the trials with probes of a $v = .60$ for the percentage of incorrect decisions revealed no main effect of *irrelevant cue relation* or *decision relation*. However, the expected interaction between *irrelevant cue*

relation and *decision relation* was significant, $F_{(1;30)} = 7.84, p < .01, \eta_p^2 = .21$, indicating that the participants made less errors if they had to change their decision from prime to probe and the irrelevant cue also changed ($M = 29.7\%, SD = 25.8\%$) than if the irrelevant cue was repeated ($M = 48.5\%, SD = 30.0\%$), $t(30) = 3.94, p < .01$. If the decision had to be repeated and the irrelevant cue was also repeated, fewer incorrect decisions were made ($M = 42.3\%, SD = 33.0\%$) than if the decision had to be repeated and the irrelevant cue changed ($M = 49.0\%, SD = 32.4\%$), $t(30) = .10, p = .34$ (see Figure 7.3a).

Furthermore, the second 2×2 analysis of variance for repeated measurements with the within-subject factors *irrelevant cue relation* (repeated versus changed) and *decision relation* (repeated versus changed) for the percentage of incorrect choices in trials with probes of a $v = .80$ revealed no significant main effect of *decision relation*, but a significant main effect of *irrelevant cue relation*, $F_{(1;30)} = 4.82, p = .04, \eta_p^2 = .14$, showing that participants made more correct decisions when they repeated their decision from prime to probe ($M = 24.3\%, SD = 17.0\%$) than when they changed it ($M = 30.0\%, SD = 20.4\%$). Again, the crucial interaction between the *irrelevant cue relation* and the *decision relation* was significant, $F_{(1;30)} = 21.21, p < .01, \eta_p^2 = .41$, indicating that the participants decided less incorrect if they had to change their decision from prime to probe and the irrelevant cue also changed ($M = 17.7\%, SD = 23.2\%$) than if the irrelevant cue was repeated ($M = 30.8\%, SD = 27.6\%$), $t(30) = 2.95, p < .01$. If the decision had to be repeated and the irrelevant cue was also repeated, fewer incorrect decisions were made ($M = 17.8\%, SD = 21.5\%$) than if the decision had to be repeated and the irrelevant cue changed ($M = 42.2\%, SD = 33.5\%$), $t(30) = 4.72, p < .01$ (see Figure 7.3b).

A $2 \times 2 \times 2$ repeated measurement analysis of variance with the within-subject factors *irrelevant cue relation* (repeated versus changed), *decision relation* (repeated versus changed) and *validity strength* ($v = .80$ versus $v = .60$) on the RTs showed no significant results. No further analyses for RTs were calculated.

7.1.3. Discussion

Like in the previous experiments in Chapter 6, I found an interaction of irrelevant cue repetition and decision repetition indicating distractor-response binding in decision making under uncertainty. In this experiment, the effect could be shown in the decision behavior – i.e. the ratio of correct decisions — instead of merely the RTs. Participants made less errors if they had to change their decision from prime to probe and the irrelevant cue also changed than if the irrelevant cue was repeated. This indicated an impairment of the decision making process because the repeated irrelevant cue retrieved the bound decision and thus, an interference occurred. However, if the decision had to be repeated and the irrelevant cue was also repeated, fewer incorrect decisions were made than if the decision had to be repeated and the irrelevant cue changed. In this case the irrelevant cue helped to make the more likely decision because the bound decision from the prime is also the more likely decision in the probe. This pattern was found both for trials with cue validity of $v = .60$ and $v = .80$.

Therefore, I clearly show that the irrelevant cue also influences the decision if it has to be made under uncertainty. Whereas the decision situation in described in Chapter 6 was close to a semantic classification task which has been used to investigate the distractor-response binding effect before (e.g., Giesen & Rothermund, 2011; Horner & Henson, 2009, 2011), with Experiment 2a I start opening a new area of behavior for investigating SR binding. Thus, not only the research field of SR binding can gain much from this novel paradigm, but these results also open up new research directions also for the area of decision making (see Section 9.2.2). In the following Experiment 2b, I will address one of these – namely, if an irrelevant information always influences the decision making process or if it depends on the validity of the relevant cues.

7.2. Experiment 2b

Experiment 2b was designed to replicate the results of Experiment 2a, and to examine the influence of the different levels of validity of the relevant cues in detail. Therefore, in Experiment 2b the validity was a between-subject factor. Note that in Experiment 2a the relevant cue in the prime was always a relevant cue from the other validity category as in the probe. Thus, the validity switched either from $v = .60$ to $v = .80$ or vice versa. There were no trials where the relevant cue was from the same validity category because repeating the validity while simultaneously keeping the same indicated decision would have also required to keep the same relevant cue, which would have introduced a confound. Therefore, I designed Experiment 2b with two relevant cues for each disease, both having the same validity. The validity was then varied as a between-subject factor instead of a within-subject factor that is, I analyzed the possible effect of distractor-response binding in a context in which the relevant cues had either a high ($v = .80$) or medium ($v = .60$) validity.

7.2.1. Methods

Participants. Further, 67 students (44 females) from the University of Trier participated in Experiment 2b. They received partial course credit for their participation. The median age of all participants was 21 (ranging from 18 to 54 years). All participants had normal or corrected-to-normal vision.

Materials. The materials and procedure were the same as in Experiment 2a with the following exceptions:

- 1) The strength of validity for the associative symptoms was realized as a between-subject factor, i.e. there were two conditions. One condition with two highly associated symptoms $v = .80$ for each of the diseases Typhoid and Diphtheria, and one condition with two less associated symptoms $v = .60$ for Typhoid and Diphtheria. These symptoms were fever and nausea for Typhoid and sore throat and dizziness

for Diphtheria. The non-associated symptoms were coughing and headache which were equally likely for both diseases $v = .50$. Therefore, these symptoms did not allow any inference about the disease the patient had. Again a relevant cue repetition and decision repetition were not confounded because there were two symptoms for each disease. Thus, a decision repetition was elicited to present the two symptoms for one disease in prime and probe.

2) The practice phase had 90 trials and the experimental phase had 243 trials.

Design. The design comprised two within-subject factors, namely irrelevant cue relation (repeated versus changed) and decision relation (repeated versus changed), as well as one between-subject factor, namely the validity of the relevant cue ($v = .80$ versus $v = .60$). Sixty-four display sequences that were relevant for the hypothesis appeared three times each. There also were 17 additional display sequences which also were repeated three times and did not follow the sequential priming pattern to avoid the recognition of a pattern by the participants.

7.2.2. Results

I calculated and cleaned the distribution of RTs in the same way as for Experiment 1a. Therefore, 14% of all RTs were discarded (first 9% were discarded because of prime errors, then 6% of the remaining trials were discarded because the RTs were outside of the fences, see Tukey, 1977). I also analyzed the numbers of incorrect decisions in the same fashion as in Experiment 1a. For the analysis of error rates only trials with correct decisions to the prime presentation were considered, i.e. 9% of all trials were discarded. Mean RTs and error rates are depicted in 7.3.

First, I performed a $2 \times 2 \times 2$ ANOVA for repeated measurements of the percentage of incorrect decisions with the factors *irrelevant cue relation* (repeated versus changed), *decision relation* (repeated versus changed), and *validity strength* ($v = .80$ versus $v = .60$). The analysis revealed no main effect of *validity strength*, $F_{(1;65)} = 2.19, p = .14, \eta_p^2 = .03$.

Tab. 7.3. Reaction times and error rates for Experiment 2b

	Decision Relation			
	Decision repetition		Decision change	
<i>v</i> = .60 condition				
Reaction times (ms)				
IRC repetition	637	(116)	675	(138)
IRC change	675	(127)	669	(111)
PE	-37	(51)	5	(59)
Error rates (%)				
IRC repetition	12	(15)	15	(22)
IRC change	18	(24)	11	(13)
PE	-6	(14)	3	(23)
<i>v</i> = .80 condition				
Reaction times (ms)				
IRC repetition	635	(95)	705	(135)
IRC change	722	(127)	703	(121)
PE	-88	(51)	2	(50)
Error rates (%)				
IRC repetition	7	(8)	11	(15)
IRC change	11	(12)	8	(10)
PE	-4	(11)	4	(15)

7. Decisions under uncertainty

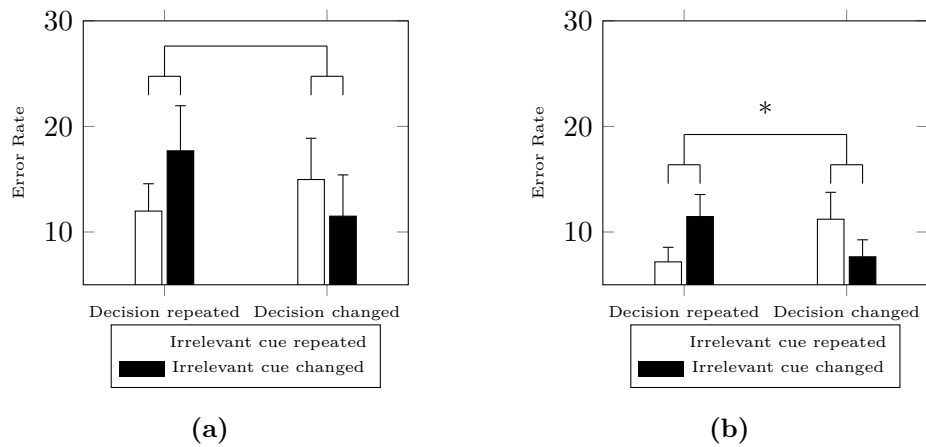


Fig. 7.4. Error rates in Experiment 2b for trials with probes with $v = 0.60$ (a) and trials with probes with $v = 0.80$ (b).

The crucial interaction between *irrelevant cue relation* and *decision relation* was significant, $F_{(1;65)} = 5.59, p = .02, \eta_p^2 = .08$, showing that the participants decided more correct if they had to change their decision from prime to probe and the irrelevant cue also changed ($M = 9.5\%, SD = 11.3\%$) than if the irrelevant cue was repeated ($M = 13.0\%, SD = 18.7\%$), $t(66) = 1.51, p = .14$. If the decision had to be repeated and the irrelevant cue was also repeated more correct decisions were made ($M = 9.5\%, SD = 11.9\%$) than if the decision had to be repeated and the irrelevant cue changed ($M = 14.4\%, SD = 19.0\%$), $t(66) = 3.26, p < .01$. The interaction between *irrelevant cue relation* and *decision relation* was not modulated by the *validity strength* of the relevant cue, $F_{(1;65)} < .04, p = .85, \eta_p^2 = .001$. No further results were significant.

For comparison with Experiment 2a, two additional 2×2 ANOVAs were computed.

A 2×2 ANOVA with the factors *irrelevant cue relation* (repeated versus changed) and *decision relation* (repeated versus changed) for the percentage of incorrect decisions in the condition with $v = .60$ revealed no main effect of *irrelevant cue relation*, *decision relation* nor any interaction between the two.

Furthermore, a second 2×2 analysis of variance for repeated measurements with the within-subject factors *irrelevant cue relation* (repeated versus changed) and *decision relation* (repeated versus changed) for percentage of incorrect decisions in the condition with $v = .80$ showed neither a significant main effect of the *irrelevant cue relation* nor any significant effect of *decision relation*. However again, the crucial interaction between *irrelevant cue relation* and *decision relation* was significant, $F_{(1,34)} = 4.17, p = .05, \eta_p^2 = .11$, showing that the participants decided correctly more often if they had to change their decision from prime to probe and the irrelevant cue also changed ($M = 7.7\%, SD = 9.5\%$) than if the irrelevant cue was repeated ($M = 11.2\%, SD = 15.1\%$), $t(34) = 1.42, p = .16$. If the decision had to be repeated and the irrelevant cue was also repeated more correct decisions were made ($M = 7.2\%, SD = 8.1\%$) than if the decision had to be repeated and the irrelevant cue changed ($M = 11.5\%, SD = 15.3\%$), $t(34) = -2.368, p = .02$.

A $2 \times 2 \times 2$ ANOVA for repeated measurements for the RTs with the within-subject factors *irrelevant cue relation* (repeated versus changed) and *decision relation* (repeated versus changed) and the between-subject factor *validity strength* ($v = .80$ versus $v = .60$) for RTs showed a significant main effect of *irrelevant cue relation*, $F_{(1,65)} = 45.79, p < .01, \eta_p^2 = .41$, showing that participants decided faster when the irrelevant cue was repeated from prime to probe ($M = 663\text{ms}, SD = 117\text{ms}$) than when it changed ($M = 693\text{ms}, SD = 120\text{ms}$), as well as a significant main effect of *decision relation*, $F_{(1,65)} = 16.53, p < .01, \eta_p^2 = .20$, showing that participants decided faster when they had to repeat their decision ($M = 668\text{ms}, SD = 114\text{ms}$) than when they had to change it ($M = 689\text{ms}, SD = 124\text{ms}$). The main effect of *validity strength* was not significant, $F_{(1,65)} = .89, p = .35, \eta_p^2 = .01$. However, the crucial interaction of *irrelevant cue relation* and *decision relation* was significant, $F_{(1,65)} = 47.92, p < .01, \eta_p^2 = .42$, indicating that participants decided faster if they had to change their decision from prime to probe and the irrelevant cue also changed ($M = 687\text{ms}, SD = 117\text{ms}$) than if the irrelevant cue was repeated ($M = 690\text{ms}, SD = 136\text{ms}$), $t(36) = .53, p = .60$. If the decision had to be repeated and the irrelevant cue

7. Decisions under uncertainty

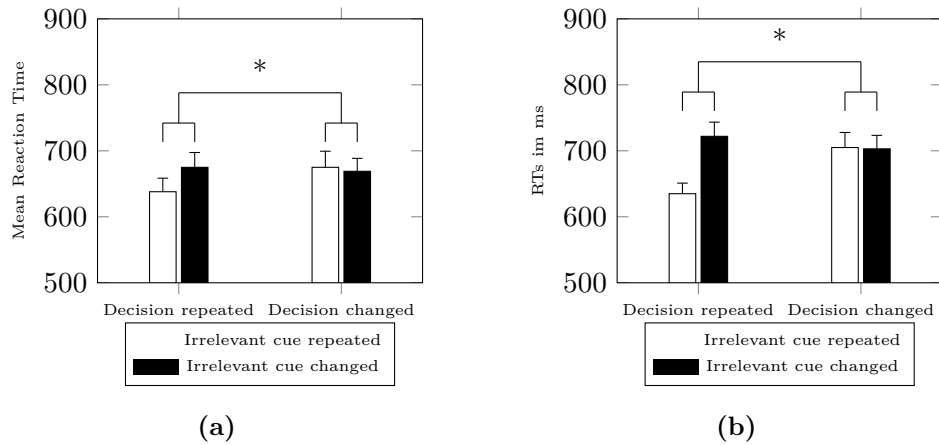


Fig. 7.5. Mean Reaction Times in Experiment 2b for trials with probes with $v = 0.60$ (a) and trials with probes with $v = 0.80$ (b).

was also repeated faster decisions were made ($M = 636\text{ms}$, $SD = 105\text{ms}$) than if the decision had to be repeated and the irrelevant cue changed ($M = 699\text{ms}$, $SD = 128\text{ms}$), $t(66) = 9.19$, $p < .01$. This was modulated by the *validity strength* of the relevant cue, $F_{(1;65)} = 6.106$, $p = .02$, $\eta_p^2 = .09$. For completeness: the interaction between *irrelevant cue relation* and *validity strength* was also significant, $F_{(1;65)} = 9.55$, $p < .01$, $\eta_p^2 = .13$. No further effects were significant.

For completeness, I also calculated two 2×2 ANOVAs for each condition independently.

A 2×2 analysis of variance for repeated measurements with the within-subject factors *irrelevant cue relation* (repeated versus changed) and *decision relation* (repeated versus changed) for RTs for the condition with relevant cues of a validity of $v = .60$ showed a significant main effect of *irrelevant cue relation*, $F_{(1;31)} = 5.59$, $p = .03$, $\eta_p^2 = .15$, showing that participants decided faster when the irrelevant cue was repeated from prime to probe ($M = 656\text{ms}$, $SD = 125\text{ms}$) than when it changed ($M = 672\text{ms}$, $SD = 117\text{ms}$), as well as a significant main effect of *decision relation*, $F_{(1;31)} = 8.81$, $p = .006$, $\eta_p^2 = .22$, showing that participants decided faster when they had to repeat their decision ($M = 656\text{ms}$, $SD = 119\text{ms}$) than when they had to change it ($M = 672\text{ms}$, $SD = 122\text{ms}$). Furthermore, the

crucial interaction between *irrelevant cue relation* and *decision relation* was significant, $F_{(1;31)} = 9.20, p < .01, \eta_p^2 = .23$, indicating that the participants decided faster if they had to change their decision from prime to probe and the irrelevant cue also changed ($M = 669\text{ms}, SD = 111\text{ms}$) than if the irrelevant cue was repeated ($M = 675\text{ms}, SD = 138\text{ms}$), $t(31) = -.50, p = .62$. If the decision had to be repeated and the irrelevant cue was also repeated faster decisions were made ($M = 637\text{ms}, SD = 116\text{ms}$) than if the decision had to be repeated and the irrelevant cue changed ($M = 675\text{ms}, SD = 127\text{ms}$), $t(31) = -4.15, p < .01$ (see Figure 7.5a).

The same 2×2 analysis of variance for repeated measurements with the within-subject factors *irrelevant cue relation* (repeated versus changed) and *decision relation* (repeated versus changed) for RTs for the condition with relevant cues of a validity of $v = .80$ showed a main effect of *irrelevant cue relation*, $F_{(1;34)} = 59.45, p < .01, \eta_p^2 = .64$, showing that participants decided faster when the irrelevant cue was repeated from prime to probe ($M = 670\text{ms}, SD = 111\text{ms}$) than when it changed ($M = 712\text{ms}, SD = 121\text{ms}$), as well as a main effect of *decision relation*, $F_{(1;34)} = 9.17, p < .01, \eta_p^2 = .21$, showing that participants decided faster if they had to repeat their decision ($M = 678\text{ms}, SD = 109\text{ms}$) than if they had to change it ($M = 704\text{ms}, SD = 126\text{ms}$). Furthermore, the crucial interaction between *irrelevant cue relation* and *decision relation* was significant, $F_{(1;34)} = 47.53, p < .01, \eta_p^2 = .58$, indicating that participants decided faster if they had to change their decision from prime to probe and the irrelevant cue also changed ($M = 703\text{ms}, SD = 121\text{ms}$) than if the irrelevant cue was repeated ($M = 705\text{ms}, SD = 135\text{ms}$), $t(34) = -0.22, p = .83$. If the decision had to be repeated and the irrelevant cue was also repeated, faster decisions were made ($M = 635\text{ms}, SD = 95\text{ms}$) than if the decision had to be repeated and the irrelevant cue changed ($M = 722\text{ms}, SD = 127\text{ms}$), $t(34) = -10.12, p < .001$ (see Figure 7.5b).

7.2.3. Discussion

Just as in the previous experiments, the distractor-response binding effect was observed. Hence, the participants decided faster if they had to change their decision from prime to probe and the irrelevant cue also changed than if the irrelevant cue was repeated. This indicated an impairment caused by the repeated irrelevant cue. If the decision had to be repeated and the irrelevant cue was also repeated, faster decisions were made than if the decision had to be repeated and the irrelevant cue changed. Thus, the irrelevant cue facilitated the decision making process. The interaction of irrelevant cue relation and decision relation was given in the RTs in the condition with moderately valid cues ($v = .60$) as well as in the condition with highly valid cues ($v = .80$), but only in the condition with a validity of $v = .80$ the interaction was found in the percentage of incorrect decisions, as well. Furthermore, the different context, i.e. here the validity of the relevant cues, did not influence the retrieval of previous decisions significantly. With the experiments in this chapter, I can clearly demonstrate that SR binding – and more precisely distractor-response binding – can influence decision behavior in situations with decisions under uncertainty. This raises the question, which constraints does distractor-response binding in decision making obey? To investigate if the same constraints as for binding processes in perception and actions apply to binding of decisions, I will test a known constraint of the distractor-response binding effect in actions: namely that irrelevant stimuli, which are semantically unrelated to the relevant stimuli or to the task-set, are not bound in an event file (Giesen & Rothermund, 2011). Should this constraint also apply to binding of irrelevant cues with decisions, this is a strong indicator of a common underlying mechanism for both binding processes.

8. Distractor-Response Binding in Decision-Making under Uncertainty: Constraints and Underlying Mechanisms

After I showed that distractor-response binding influences deterministic decision making and decision making under uncertainty, I now want to challenge these findings. The following experiments analyze, on the one hand, under which circumstances distractor-response binding no longer influences decision making and on the other hand what exactly is bound.

Therefore, Experiment 3a tests if distractor-response binding still plays a role if the irrelevant and relevant cue come from unrelated semantic categories. In previous research on distractor-response binding it was shown that distractors have only an effect, if distractor and target are from the same semantic category (Giesen & Rothermund, 2011). In Experiment 3b I analyzed if distractor-response binding only influences decision making if the participants decided under time pressure. In Section 2.2 I established possible theoretical links between distractor-response binding mechanisms and routine building mechanisms. Since Betsch et al. (2004) could show that participants are more likely to choose routine behavior if they are under time pressure, I also expected time pressure to influence distractor-response binding in decision making. I designed Experiment 3c to investigate, if the decision or the motor program is bound. In Experiment 3d I examined

if only decisions are influenced by distractor-response binding or if this effect generalizes to the confidence in the decision.

8.1. Experiment 3a

Experiment 3a was designed to investigate if distractor-response binding in decision making follows the same constraints as in simple classification tasks. Therefore, I tested if the moderating mechanism of semantic grouping (Giesen & Rothermund, 2011) shows the same influence in decision making tasks like in typical priming tasks. Thus, I did not longer present the irrelevant cue in form of an irrelevant symptom with a validity of 50% but instead I presented the day of the patients' visit. This cue has something to do with the diagnosis scene but is semantically unrelated to the relevant cue for the decision. According to previous findings about stimulus-response binding, features with no semantic relation to the current task-set, are not bound together (Frings & Rothermund, 2011; Giesen & Rothermund, 2011; Hommel, 2005).

Furthermore, outside the lab, it is rare that the actual validities of the cues are known with certainty. Instead, we have to rely on experience to learn the validities (see Section 4.1.2). This means that our knowledge about cue validities is itself just an estimate. Since the validities of cues which have been experienced to be irrelevant may have been wrongly estimated, these cues may later actually prove to be relevant. Hence, it makes sense to include these cues as part of an event file (see Moeller & Frings, 2014c, for a similar idea about the helpfulness of irrelevant information). However, it is not feasible to include any irrelevant information in an event file, on the hunch that it may actually prove to be relevant. Instead, only such information, which may prove useful based on a semantic relation to the decision problem at hand should be included. Hence, Experiment 3a both tests common constraints between distractor-response binding in classification and in decision making, but also tests the ecological rationality of distractor-response binding mechanisms in decision making.

8.1.1. Methods

Participants. Further, thirty-five students (22 females) from the University of Trier participated in Experiment 3a. They received partial course credit for their participation. The median age of all participants was 21 (ranging from 19 to 28 years). The data of one participant was excluded because their incorrect decisions of 44% in the practice trials and 32% in the prime decisions was an outlier with respect to the distribution of the whole sample (Tukey, 1977). All participants had normal or corrected-to-normal vision.

Materials. The materials and procedure were the same as in Experiment 2a with the following exceptions: 1) The irrelevant cue symptoms were exchanged with the day of the visit of the patient. The patient visited either Tuesday or Wednesday. 2) The irrelevant cue was always presented above the relevant cue like in the series of experiments in Chapter 6. 3) The practice phase had 80 trials and the experimental phase had 96 trials.

Design. The design comprised three within-subject factors, namely *irrelevant cue relation* (repeated versus changed), *decision relation* (repeated versus changed), and *validity strength* of the relevant cue in the probe ($v = .80$ versus $v = .60$). The factors were fully balanced, i.e. all possible combinations of factors were presented 8 times. There also were 32 additional trials which did not follow the sequential priming pattern to avoid the recognition of a pattern by the participants.

8.1.2. Results

I calculated and cleaned the distribution of RTs in the same way as for Experiment 1a. 14% of all RTs were discarded (first 6% were discarded because of prime errors, then 9% of the remaining trials were discarded because the RTs were outside of the fences, see Tukey, 1977). I also analyzed the number of incorrect decisions in the same fashion as in Experiment 1a. For the analysis of error rates only trials with correct decisions to the

Tab. 8.1. Reaction times and error rates for Experiment 3a

	Decision Relation			
	Decision repetition		Decision change	
<i>v</i> = .60 condition				
Reaction times (ms)				
IRC repetition	615	(163)	596	(108)
IRC change	610	(146)	647	(121)
PE	5	(109)	-50	(85)
Error rates (%)				
IRC repetition	16	(21)	20	(27)
IRC change	19	(22)	17	(24)
PE	-3	(22)	3	(16)
<i>v</i> = .80 condition				
Reaction times (ms)				
IRC repetition	564	(113)	580	(111)
IRC change	554	(86)	586	(114)
PE	10	(111)	-6	(86)
Error rates (%)				
IRC repetition	10	(16)	14	(22)
IRC change	11	(17)	12	(21)
PE	0	(17)	2	(11)

prime presentation were considered, i. e., 6% of all trials were discarded. Mean RTs and error rates are depicted in Table 8.1.

Separate analyses for RTs and number of incorrect decisions were computed. Pillai's trace was taken as a criterion for all variance analyses of repeated measurements.

A $2 \times 2 \times 2$ repeated measurements ANOVA with the within-subject factors *irrelevant cue relation* (repeated versus changed), *decision relation* (repeated versus changed), and *validity strength* ($v = .60$ vs. $v = .80$) for the percentage of incorrect decisions revealed a main effect of *validity strength*, $F_{(1;33)} = 14.08, p = .001, \eta_p^2 = .30$, showing that participants made less incorrect decisions when the validity in the prime was .60 and in the probe was .80 ($M = 11.8\%, SD = 12.3\%$) than vice versa ($M = 17.8\%, SD = 14.1\%$). The interaction between *decision relation* and *irrelevant cue relation* was not significant, $F_{(1;33)} = 1.93, p = .18, \eta_p^2 = .06$. No further results were significant.

Because of the difference in the number of incorrect answers between trials with a validity strength of $v = .60$ and a validity strength of $v = .80$, two additional 2×2 ANOVAs were computed separately for the trials with a validity of $v = .80$ and the trials with a validity of $v = .60$ condition. However, these analyzes showed no significant results.

A $2 \times 2 \times 2$ ANOVA for repeated measurements with the within-subject factors *irrelevant cue relation* (repeated versus changed), *decision relation* (repeated versus changed), and *validity strength* ($v = .60$ versus $v = .80$) for RTs showed a significant main effect of *validity strength*, $F_{(1;33)} = 15.85, p < .01, \eta_p^2 = .32$, showing that participants decided faster when the validity in the prime was $v = .60$ and in the probe $v = .80$ ($M = 571\text{ms}, SD = 87\text{ms}$) than vice versa ($M = 617\text{ms}, SD = 119\text{ms}$). Furthermore, the crucial interaction of *irrelevant cue relation* and *decision relation* was significant, $F_{(1;33)} = 4.48, p = .04, \eta_p^2 = .12$. So, the participants decided slower if they had to change their decision from prime to probe and the irrelevant cue also changed ($M = 616\text{ms}, SD = 119\text{ms}$) than if the irrelevant cue was repeated ($M = 588\text{ms}, SD = 100\text{ms}$), $t(33) = -3.00, p < .01$. On the other hand if the decision had to be repeated and the irrelevant cue was also repeated

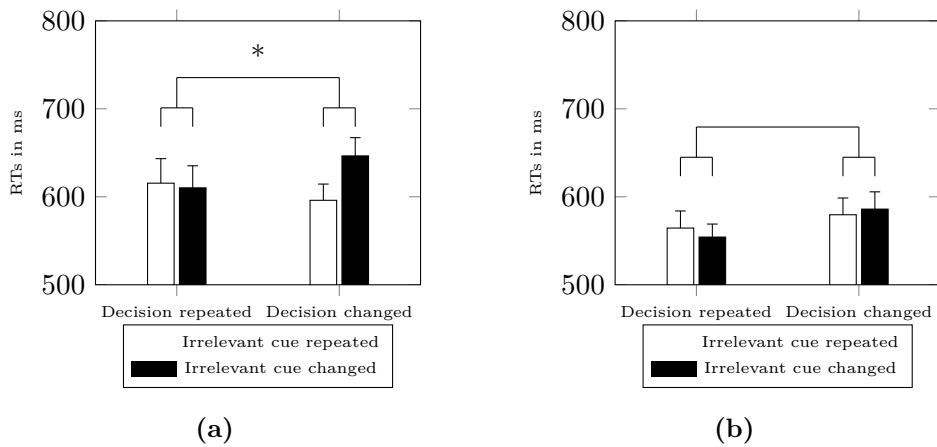


Fig. 8.1. Reaction times in ms in Experiment 3a for trials with probes with $v = 0.60$ (a) and trials with probes with $v = 0.80$ (b).

slower decisions were made ($M = 590\text{ms}$, $SD = 129\text{ms}$) than if the decision had to be repeated and the irrelevant cue changed, $t(33) = .50$, $p = .62$. Hence, the analysis revealed the opposite interaction pattern as in the previous experiments. No further result was significant.

To test for the influence of the validity, two additional 2×2 ANOVAs separately for trials with validity $v = .60$ and $v = .80$ were computed.

The first 2×2 ANOVA with the within-subject factors *irrelevant cue relation* (repeated versus changed) and *decision relation* (repeated versus changed) for trials with $v = .60$ revealed a significant interaction between *irrelevant cue relation* and *decision relation*, $F_{(1;33)} = 5.42$, $p = .03$, $\eta_p^2 = .14$, indicating that participants decided slower if the decision had to be repeated and the irrelevant cue also was repeated ($M = 615$, $SD = 163$) than if the irrelevant cue was changed ($M = 610$, $SD = 146$), $t(33) = .28$, $p = .78$. On the other hand participants decided faster if the decision changed and the irrelevant cue had to be repeated ($M = 596$, $SD = 108$), than if the irrelevant cue was changed ($M = 647$, $SD = 121$), $t(33) = -3.45$, $p < .01$. Hence, again this interaction was in the opposite direction as expected (see Figure 8.1a).

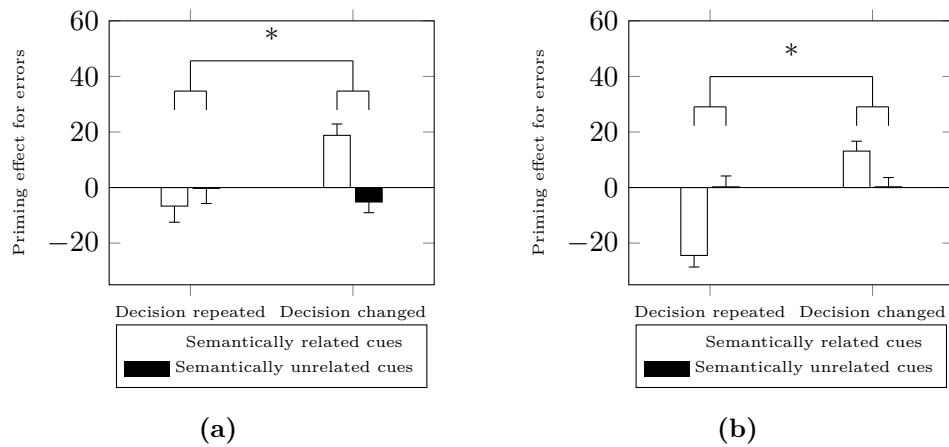


Fig. 8.2. Comparison of the priming effect (irrelevant cue repeated trials minus irrelevant cue changed trials) for semantically related cues (Experiment 2a) and semantically unrelated cues (Experiment 3a). (a) shows trials with $v = .60$ and (b) shows trials with $v = .80$.

The second 2×2 ANOVA with the within-subject factors *irrelevant cue relation* (repeated versus changed) and *decision relation* (repeated versus changed) for trials with $v = .60$ revealed neither significant main effects nor an interaction between *irrelevant cue relation* and *decision relation* (see Figure 8.1b).

Comparison of the data of Experiments 2a and 3a. To test if there was an actual influence of the semantic relation between distractor and the decision task, I combined the data of Experiment 2a (relevant cue and irrelevant cue were from the same semantic category because they were both symptoms) and Experiment 3a (the semantic category of the relevant cue and irrelevant cue were unrelated – symptom versus day of patient’s visit).

A $2 \times 2 \times 2 \times 2$ analysis of variance for repeated measurements with the within subject factors *irrelevant cue relation* (repeated versus changed), *decision relation* (repeated versus changed), *validity strength* ($v = .60$ versus $v = .80$), and *semantic relation* (related versus unrelated) for percentage of incorrect decisions revealed a significant main effect of *validity strength*, $F_{(1,64)} = 24.99, p < .01, \eta_p^2 = .28$, showing that participants made

8. Constraints and Underlying Mechanisms

less incorrect decisions when the validity in the prime was .60 and in the probe was .80 ($M = 19.7\%$, $SD = 17.2\%$) than vice versa ($M = 29.9\%$, $SD = 21.0\%$). Furthermore, the main effect of *semantic relation* was significant, $F_{(1,64)} = 27.85$, $p < .01$, $\eta_p^2 = .30$, indicating that participants were more likely to decide correctly ($M = 16\%$, $SD = 14\%$) when the irrelevant cue was unrelated to the relevant cue than if it was related ($M = 35\%$, $SD = 15\%$). No further main effects were significant. There also was an interaction between *irrelevant cue relation* and *decision relation*, $F_{(1,64)} = 20.51$, $p < .01$, $\eta_p^2 = .24$, indicating that participants made more correct decisions when they had to repeat their decisions and the irrelevant cue was repeated ($M = 22.3\%$, $SD = 22.8\%$) than if the irrelevant cue changed ($M = 29.6\%$, $SD = 26.9\%$), $t(65) = 2.50$, $p = .02$. However, when they had to change their decision and the irrelevant cue was repeated they made more incorrect decisions ($M = 28.1\%$, $SD = 25.9\%$) than if the irrelevant cue changed ($M = 19.2\%$, $SD = 20.9\%$), $t(65) = 4.35$, $p < .01$. Importantly, this interaction was significantly modulated by the *semantic relation*, $F_{(1,64)} = 14.47$, $p < .01$, $\eta_p^2 = .18$ showing that the difference in priming effects for trials where the decision was repeated to trials where the decision changed was significantly larger if the cues were semantically related, than if they were unrelated to the task (see Figure 8.2). For completeness, I also report the following other significant interactions. There was a significant interaction between *validity strength* and *semantic relation*, $F_{(1,64)} = 5.19$, $p = .03$, $\eta_p^2 = .08$ and a significant interaction between *validity strength* and *irrelevant cue relation*, $F_{(1,64)} = 6.18$, $p = .02$, $\eta_p^2 = .09$. No further effects were significant.

For reason of completeness I also computed a $2 \times 2 \times 2 \times 2$ analysis of variance for repeated measurements with the within subject factors *irrelevant cue relation* (repeated versus changed), *decision relation* (repeated versus changed), *validity strength* ($v = .60$ versus $v = .80$), and *semantic relation* (related versus unrelated) for the RTs. The main effect of *validity strength* was significant, $F_{(1,64)} = 5.19$, $p = .03$, $\eta_p^2 = .08$, showing that participants decided faster when the validity in the prime was $v = .60$ and in the probe

$v = .80$ ($M = 698\text{ms}$, $SD = 185\text{ms}$) than vice versa ($M = 745\text{ms}$, $SD = 209\text{ms}$). Also, the main effect for *semantic relation* was significant, $F_{(1;64)} = 22.42$, $p < .01$, $\eta_p^2 = .27$, showing that participants decided faster when the irrelevant cue was unrelated ($M = 626\text{ms}$, $SD = 128\text{ms}$) than if it was related ($M = 831\text{ms}$, $SD = 199\text{ms}$).

8.1.3. Discussion

In contrast to the previous experiments Experiment 3a showed no significant interaction between irrelevant cue relation and decision relation in the number of incorrect decisions (for RTs a significant interaction in the opposite direction was found). The comparison of the data from Experiment 3a with Experiment 2a revealed that the effects are significantly different for the percentage of incorrect decisions. Thus, these results can be interpreted as evidence that the irrelevant cues are only encoded together with the decision in an event file if there is a semantic relation between the cue and the decision task. This evidence is well in line with results from other studies on SR binding (e. g., Giesen & Rothermund, 2011). No SR binding was expected in Experiment 3a, since the same mechanisms of (semantic) grouping which moderates distractor-response binding in classification tasks, should also influence the distractor-response binding effect in decision making tasks. Thus, consistent with previous research on SR binding (Giesen & Rothermund, 2011), the irrelevant cue in Experiment 3a did not influence the response. According to the result of Experiment 3a, not every irrelevant information available at encoding is integrated in the event file and can influence the following decision making process. The irrelevant cue has to fulfill some criteria like semantic overlap for being integrated in an event file. This hints at a common underlying mechanism responsible both for classical distractor response binding and distractor response binding in decision tasks. Somewhat unexpectedly I found a reversed binding effect in the RTs. Taking a closer look at the RTs in the different conditions, one possibility is that participants actually used the irrelevant cue in some way strategically. In fact, the condition in which the decision changes but the irrelevant

cue repeats was unusually fast (but is typically expected to be slow as the repeated irrelevant cue will retrieve an incompatible response). Perhaps participants just tried to be careful not to integrate completely uninformative information like the day of week into their decision (“Be careful now – only because the last patient on Wednesday had Typhus, this does not indicate that the current one also has it – he probably does not have it as Wednesday has nothing to do with Typhus!”). However, the interaction was mostly caused by the significant difference in trials where the decision changed with a validity of $v = .60$. In this case participants were faster if the decision changed and the irrelevant cue was repeated. Hence, another possible explanation may be that the day of the week was inhibited (Houghton & Tipper, 1994) because it was already identified as irrelevant in the prime, so that a repetition of the irrelevant cue in this case leads to facilitation. However, this explanation leaves the question, why inhibition only appeared in trials with $v = .60$ where the decision was changed, but not in other trials where the irrelevant cue was repeated. On the other hand, the probability that at least one of the t-tests above would produce a type I error at $\alpha = .05$, even if the null hypothesis is true for all of them is about 19%. Hence, the difference in these specific trials may be due to statistical fluctuations.

Moreover, the analysis showed that participants were generally faster in the condition where the irrelevant cues had no semantic relation. This shows that generally the task in this condition was simpler. Also, this shows that participants used a strategy, which integrated both the relevant as well as the irrelevant cue. Furthermore, Glöckner and Betsch (2012) present evidence that the speed with which a decision can be done, does not depend on the number of cues, but rather on the coherence of all cues. This is taken as evidence that decisions are based on Gestalt processes (see Section 4.2.2), which require less work, if the Gestalt is more coherent. In case of semantically unrelated cues, Gestalt laws indicate that the semantically unrelated cue will not be integrated into the Gestalt, leading to reduced time required to build up a coherent Gestalt.

Nevertheless, one could still criticize that in the previous experiments the findings could also be explained by other factors. While the participants should learn through the practice trials that some of the symptoms are irrelevant, they may still have perceived as relevant. Another interpretation of the current findings could be that by using the day of the week as a irrelevant cue, participants could more easily learn that this cue was irrelevant. To test if the irrelevant cue was really learned correctly I asked participants how useful they rated the cues for the task in Experiment 3d.

8.2. Experiment 3b

Experiment 3b was designed to investigate if the distractor-response binding in decision making only occurs under time pressure or even if the participants had the possibility to use all their cognitive resources. I hypothesized that the automatic process of SR binding (Hommel, 2005; Hommel & Colzato, 2004, 2009) cannot be overruled even when participants can use their full cognitive resources (Kahneman, 2011). The other experiments presented in this thesis forced the participants to decide under time pressure, hence limiting the available cognitive resources (Kahneman, 2011).

However, Betsch et al. (2004) showed that people are more likely to rely on routinized behavior under strong than under mild time pressure. As the theory presented in Chapter 2 indicates that event file mechanisms are most likely a part of routine building mechanisms, I also expected at least a change in the strength of distractor-response binding in Experiment 3b.

8.2.1. Methods

Participants. Further, thirty students (26 females) from the University of Trier participated in Experiment 3b. They received partial course credit for their participation. The median age of all participants was 20 (ranging from 18 to 30 years). All participants had normal or corrected-to-normal vision.

Materials. The materials and procedure were the same as in Experiment 2a (see Figure 7.2 on page 103) with one exception: the participants were instructed that their quality instead of their speed of a decision was evaluated. Thus, they should take time to make their decisions. They could take all the time they wanted to decide about the diagnosis. Therefore, no request to decide faster popped out after 2500ms .

Design. The design comprised three within-subject factors, namely *irrelevant cue relation* (repeated versus changed), *decision relation* (repeated versus changed), and *validity strength* of the relevant cue in the probe ($v = .80$ versus $v = .60$). The factors were fully balanced, i.e. all possible combinations of factors were presented 8 times. There also were 68 additional trials which did not follow the sequential priming pattern to avoid the recognition of a pattern by the participants. These trials were not included in the analyses. In all trials included in the later analysis the relevant cue was always changed between prime and probe. At the same time the validity was always changed between prime and probe. Hence, for a probe with $v = .80$ the prime would indicate a response with a likelihood of $v = .60$ and vice versa.

8.2.2. Results

I analyzed the data in the same way as in Experiment 1a. Therefore, 12% of all RTs were discarded (first 9% were discarded because of prime errors, then 3% percent of the remaining trials were discarded because the RTs were outside of the fences, see Tukey, 1977). For the analysis of error rates only trials with correct answers to the prime

Tab. 8.2. Reaction times and error rates for Experiment 3b

	Decision Relation			
	Decision repetition		Decision change	
<i>v</i> = .60 condition				
Reaction times (ms)				
IRC repetition	2973	(1100)	2994	(1173)
IRC change	3031	(1031)	3074	(1124)
PE	-57	(521)	-80	(593)
Error rates (%)				
IRC repetition	8	(14)	15	(24)
IRC change	9	(18)	15	(24)
PE	0	(11)	0	(16)
<i>v</i> = .80 condition				
Reaction times (ms)				
IRC repetition	2705	(970)	2908	(1087)
IRC change	2797	(1029)	3026	(1130)
PE	-92	(473)	-118	(570)
Error rates (%)				
IRC repetition	5	(12)	7	(12)
IRC change	8	(17)	4	(11)
PE	-2	(11)	2	(10)

presentation were considered, i.e. 9% of all trials were discarded. Mean RTs and error rates are depicted in Table 8.2.

Separate analyses for RTs and number of incorrect decisions were computed. Furthermore, Pillai's trace was taken as a criterion for all variance analyses of repeated measurements.

First, I performed a $2 \times 2 \times 2$ ANOVA of the percentage of incorrect decisions with the factors *irrelevant cue relation* (repeated versus changed), *decision relation* (repeated versus changed), and *validity strength* ($v = .80$ versus $v = .60$). The analysis revealed a main effect of *validity strength* $F_{(1;29)} = 5.10, p = .03, \eta_p^2 = .15$, showing that participants made less incorrect decisions when the validity in the prime was $v = .60$ and in the probe was $v = .80$ ($M = 6.3\%, SD = 10.0\%$) than vice versa ($M = 12.0\%, SD = 14.2\%$). However, the expected interaction between *irrelevant cue relation* and *decision relation* was not significant, $F_{(1;29)} = 1.45, p = .24, \eta_p^2 = .05$. For completeness: the interaction between *validity strength* and *decision relation* was significant, $F_{(1;29)} = 5.71, p = .02, \eta_p^2 = .17$. No further results were significant.

Because of the difference in the number of incorrect answers between trials with $v = .60$ and $v = .80$, two additional 2×2 ANOVAs were computed separately for the $v = .80$ and the $v = .60$ condition.

A 2×2 ANOVA with the factors *irrelevant cue relation* (repeated versus changed) and *decision relation* (repeated versus changed) exclusively on the trials with probes of a $v = .60$ for the percentage of incorrect decisions revealed no significant results (see Figure 8.3a).

The second 2×2 analysis of variance for repeated measurements with the within-subject factors *irrelevant cue relation* (repeated versus changed) and *decision relation* (repeated versus changed) for the numbers of incorrect choices in trials with probes of a $v = .80$ revealed a significant interaction between the *irrelevant cue relation* and the *decision relation*, $F_{(1;29)} = 4.77, p = .04, \eta_p^2 = .14$, indicating that the participants

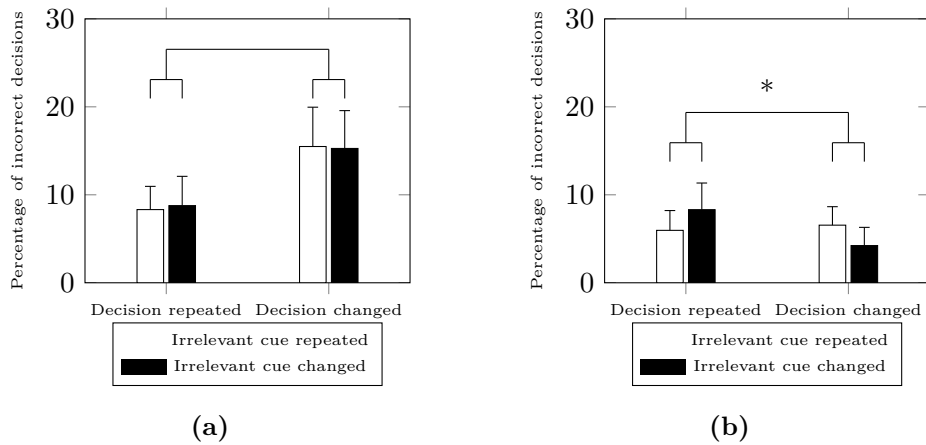


Fig. 8.3. Percentage of incorrect decisions in Experiment 3b for trials with probes with $v = 0.60$ (a) and trials with probes with $v = 0.80$ (b).

decided less incorrect if they had to change their decision from prime to probe and the irrelevant cue also changed ($M = 4.2\%$, $SD = 11.3\%$) than if the irrelevant cue was repeated ($M = 6.6\%$, $SD = 11.5\%$), $t(29) = 1.13$, $p = .27$. If the decision had to be repeated and the irrelevant cue was also repeated, fewer incorrect decisions were made ($M = 6.0\%$, $SD = 12.3\%$) than if the decision had to be repeated and the irrelevant cue changed ($M = 8.3\%$, $SD = 16.6\%$), $t(29) = 1.28$, $p = .21$ (see Figure 8.3b).

A $2 \times 2 \times 2$ analysis of variance for repeated measurements with the within-subject factors *irrelevant cue relation* (repeated versus changed), *decision relation* (repeated versus changed) and *validity strength* ($v = .80$ versus $v = .60$) of the RTs showed a significant main effect of *decision relation*, $F_{(1;29)} = 6.70$, $p = .02$, $\eta_p^2 = .13$, indicating that participants decided faster when they repeated their decision ($M = 2895\text{ms}$, $SD = 1030\text{ms}$) as when they changed it ($M = 2982\text{ms}$, $SD = 1019\text{ms}$), and a significant main effect of *validity strength*, $F_{(1;29)} = 5.15$, $p = .03$, $\eta_p^2 = .15$, showing that participants decided faster when the validity in the prime was $v = .60$ and in the probe $v = .80$ ($M = 2859\text{ms}$, $SD = 1003\text{ms}$) than vice versa ($M = 3018\text{ms}$, $SD = 1057\text{ms}$). The crucial interaction between *decision*

8. Constraints and Underlying Mechanisms

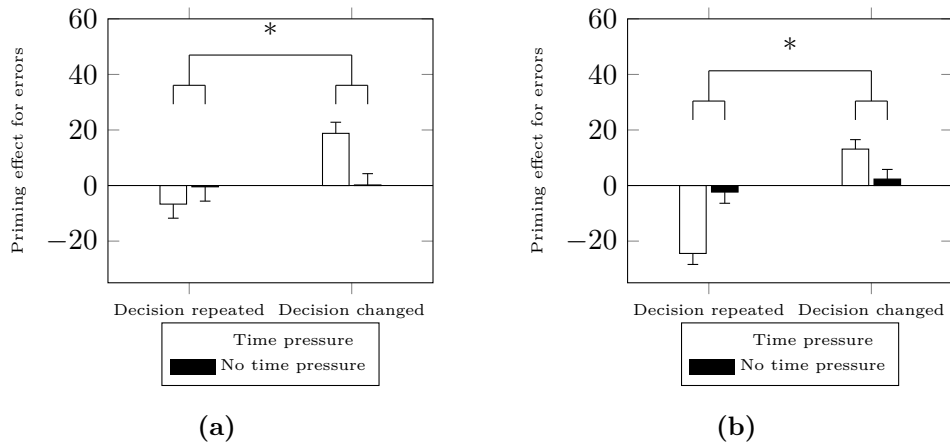


Fig. 8.4. Comparison of the priming effect (irrelevant cue repeated trials minus irrelevant cue changed trials) for decisions under time pressure (Experiment 2a) and decision without time pressure (Experiment 3b). (a) shows trials with $v = .60$ and (b) shows trials with $v = .80$.

relation and *irrelevant cue relation* was not significant, $F_{(1;29)} = .08, p = .79, \eta_p^2 < .01$. No further effects were significant.

Comparison of the data of Experiments 2a and 3b. To test if there was an actual influence of the missing time pressure for the decision task, I combined the data of Experiment 2a (here the participants were instructed to decide as fast as possible) and Experiment 3b (the participants were instructed to take all the time they needed for the decisions).

A $2 \times 2 \times 2 \times 2$ analysis of variance for repeated measurements with the factors *irrelevant cue relation* (repeated versus changed), *decision relation* (repeated versus changed), *validity strength* ($v = .60$ versus $v = .80$), and *time pressure* (with time pressure versus without time pressure) for percentage of incorrect decisions revealed a significant main effect of *validity strength*, $F_{(1;59)} = 18.71, p < .01, \eta_p^2 = .24$, showing that participants made less incorrect decisions when the validity in the prime was $.60$ and in the probe was $.80$ ($M = 16.9\%$, $SD = 17.6\%$) than vice versa ($M = 27.4\%$, $SD = 23.1\%$). Furthermore, the main effect of the *time pressure* was significant, $F_{(1;59)} = 61.85, p < .01, \eta_p^2 = .51$, indicating that

participants were more likely to decide correctly ($M = 9.1\%$, $SD = 10.2\%$) when they had no time pressure than if they had to decide under time pressure ($M = 34.8\%$, $SD = 14.8\%$). No further main effects were significant. There also was an interaction between *irrelevant cue relation* and *decision relation*, $F_{(1;59)} = 20.01, p < .01, \eta_p^2 = .25$, indicating that participants made more correct decisions when they had to repeat their decisions and the irrelevant cue was repeated ($M = 18.8\%$, $SD = 21.0\%$) than if the irrelevant cue changed ($M = 27.4\%$, $SD = 28.5\%$), $t(60) = 3.16, p < .01$. However, when they had to change their decision and the irrelevant cue was repeated they made more incorrect decisions ($M = 25.61\%$, $SD = 24.9\%$) than if the irrelevant cue changed ($M = 16.8\%$, $SD = 19.2\%$), $t(60) = 9.92, p < .01$. This interaction was significantly modulated by the factor of *time pressure*, $F_{(1;59)} = 14.24, p < .01, \eta_p^2 = .19$, showing that the interaction between *irrelevant cue relation* and *decision relation* was stronger when the participants had to decide under time pressure (see Figure 8.4). For completeness, I also report the following other significant interactions. There was a significant interaction between *validity strength* and *time pressure*, $F_{(1;59)} = 3.89, p = .05, \eta_p^2 = .06$, a significant interaction between *validity strength* and *irrelevant cue relation*, $F_{(1;59)} = 5.14, p = .03, \eta_p^2 = .08$, and a significant interaction between *irrelevant cue relation*, *validity strength*, and *time pressure*, $F_{(1;59)} = 5.33, p = .03, \eta_p^2 = .08$. No further effects were significant.

For reason of completeness I also computed a $2 \times 2 \times 2 \times 2$ analysis of variance for repeated measurements with the factors *irrelevant cue relation* (repeated versus changed), *decision relation* (repeated versus changed), *validity strength* ($v = .60$ versus $v = .80$), and *time pressure* (with time pressure versus without time pressure) for the RTs¹. The main effect of *decision relation* was significant, $F_{(1;58)} = 6.61, p = .01, \eta_p^2 = .10$, showing that participants decided faster when they repeated their decision ($M = 1858\text{ms}$, $SD = 1234\text{ms}$) than if they changed their decision ($M = 1925\text{ms}$, $SD = 1303\text{ms}$). Further, the main effect of *validity strength* was significant, $F_{(1;58)} = 6.21, p = .02, \eta_p^2 = .10$, showing that participants

¹Note that for this analysis one participant was excluded because of missing data in one of the categories.

decided faster when the validity in the prime was $v = .60$ and in the probe $v = .80$ ($M = 1845\text{ms}$, $SD = 1235\text{ms}$) than vice versa ($M = 1938\text{ms}$, $SD = 1310\text{ms}$). Unsurprisingly, the main effect for *time pressure* was significant, $F_{(1;58)} = 121.83$, $p < .01$, $\eta_p^2 = .68$, showing that participants decided faster when they had to decide under time pressure ($M = 878\text{ms}$, $SD = 226\text{ms}$) than if they had no time pressure ($M = 2938\text{ms}$, $SD = 1012\text{ms}$). Moreover, the interaction between *decision relation* and *time pressure* was significant, $F_{(1;58)} = 5.04$, $p = .03$, $\eta_p^2 = .08$. No further results were significant.

8.2.3. Discussion

As expected, there was no distractor-response binding effect in the RTs. For trials with probes with validity $v = .80$, however, a distractor-response binding effect could be found in the number of incorrect decisions, showing that automatic retrieval of the event file could not be fully inhibited. For probes with validity $v = .60$ no distractor-response binding could be found. This finding is in line with the results from Experiment 2b, in which the distractor-response binding effect was also only found for probes with $v = .80$. However, in the detailed analysis of the number of incorrect decisions separately for each validity, none of the t-tests showed a significant difference between the tested factor combinations. This may also indicate that there was a type I error in this analysis and distractor-response binding was suppressed by removing the time limit.

The comparison between Experiments 2a and 3b showed that distractor-response binding was reduced by eliminating the time pressure. This showed that deliberate processing can overrule automatic processes like event file retrieval at least to some extent.

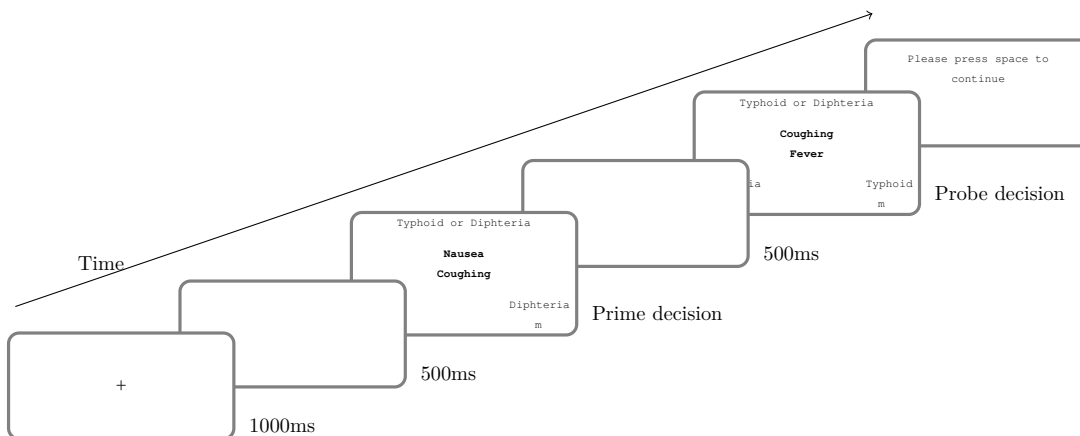


Fig. 8.5. The sequence of events of one trial in Experiment 3c. Stimuli are not drawn to scale.

8.3. Experiment 3c

Experiment 3c was designed to investigate if distractor-response binding in decision making describes the binding of the mental representation of the decision or if the response key used to communicate the decision is bound together with the irrelevant cue. In the previous experiments the decision and the key used to give the decision were the same over all prime-probe sequences. Hence, the decision and the key used to communicate the decision could not be disentangled. In Experiment 3c I presented prime-probe sequences where the key association switched between prime and probe. I expected that the switch does not modulate the distractor-response binding.

8.3.1. Methods

Participants. Further, sixty-three students² (53 females) from the University of Trier participated in Experiment 3c. They received partial course credit for their participation. The median age of all participants was 20 (ranging from 18 to 28 years). All participants had normal or corrected-to-normal vision.

²Because Experiment 3c included one addition factor, the number of participants was increased.

Materials. The materials and procedure were similar to Experiment 2b of the condition with the validity of .80 with one exception (see Figure 8.5): Contrary to the previous experiments the participants were not instructed which key they had to press for which disease. Instead in the displays' lower left and right corner they were indicated if they should press *c* for Typhoid and *m* for Diphtheria or vice versa. In half of the trials the key association switched from prime to probe.

Design. The design comprised three within-subject factors, namely *irrelevant cue relation* (repeated versus changed), *decision relation* (repeated versus changed), and *key association* (repeated versus changed). 128 display sequences that were relevant for the hypothesis appeared 2 times. There also were 34 additional display sequences which also where repeated 2 times and did not follow the sequential priming pattern to avoid the recognition of a pattern by the participants³.

8.3.2. Results

I calculated and cleaned the distribution of RTs in the same way as for Experiment 1a. Therefore, 18% of all RTs were discarded (first 13% were discarded because of prime errors, then 5% of the remaining trials were discarded because the RTs were outside of the fences, see Tukey, 1977). I also analyzed the numbers of incorrect decisions in the same fashion as in Experiment 1a. For the analysis of error rates only trials with correct decisions to the prime presentation were considered, i.e. 13% of all trials were discarded. Mean RTs and error rates are depicted in Table 8.3.

Separate analyses for RTs and number of incorrect decisions were computed. Furthermore, Pillai's trace was taken as a criterion for all variance analyses of repeated measurements.

³The number of different display sequence was twice as high as in Experiment 2b, after which this experiment was modeled, because half of the display sequence included a key change and the other half did not.

Tab. 8.3. Reaction times and error rates for Experiment 3c

	Decision Relation			
	Decision repetition		Decision change	
No key association change				
Reaction times (ms)				
IRC repetition	1052	(191)	1079	(234)
IRC change	1150	(213)	1073	(210)
PE	-97	(124)	5	(104)
Error rates (%)				
IRC repetition	10	(18)	10	(16)
IRC change	11	(16)	8	(17)
PE	-1	(16)	2	(18)
key association change				
Reaction times (ms)				
IRC repetition	1200	(245)	1151	(279)
IRC change	1179	(258)	1175	(241)
PE	21	(139)	-24	(153)
Error rates (%)				
IRC repetition	21	(25)	13	(19)
IRC change	16	(21)	21	(27)
PE	5	(15)	-8	(21)

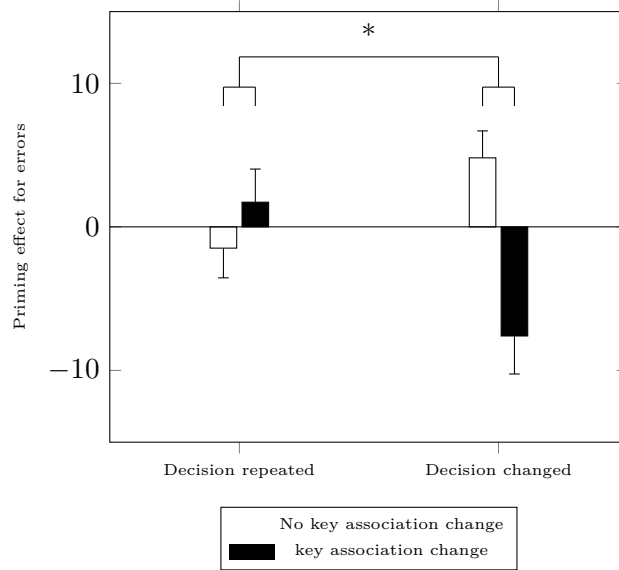


Fig. 8.6. Comparison of the priming effect (irrelevant cue repeated trials minus irrelevant cue changed trials) for trials with no key association change and trials with key association change on the error rates in Experiment 3c.

First, I computed a $2 \times 2 \times 2$ analysis of variance for repeated measurements with the within-subject factors *irrelevant cue relation* (repeated versus changed), *decision relation* (repeated versus changed), and *key association* (repeated versus changed) for the percentage of incorrect decisions. The main effect of *decision relation* was significant, $F_{(1,62)} = 5.31, p = .03, \eta_p^2 = .08$, showing that participants made more correct decisions when they changed their decision from prime to probe ($M = 13.1\%, SD = 15.4\%$) as when they had to repeat their decision ($M = 14.4\%, SD = 16.9\%$), as well as the main effect of *key association*, $F_{(1,62)} = 19.90, p < .001, \eta_p^2 = .24$, showing that the participants made more correct decisions when the key association did not switch from prime to probe ($M = 9.8\%, SD = 13.7\%$) as when the key association switched ($M = 17.8\%, SD = 20.9\%$). However, the crucial interaction of *irrelevant cue relation* and *decision relation* revealed no significant result, $F_{(1,62)} = 1.95, p = .17, \eta_p^2 = .03$. The three-way interaction between *irrelevant cue relation*, *decision relation*, and *key*

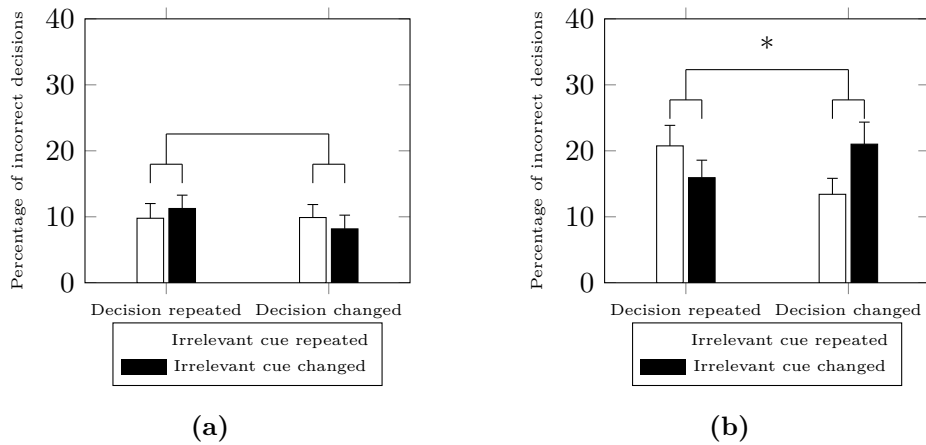


Fig. 8.7. Percentage of incorrect decisions in Experiment 3c for trials without key association change (a) and trials with key association change (b).

association was significant, $F_{(1;62)} = 11.60, p < .01, \eta_p^2 = .16$ (see Figure 8.6). No further results were significant.

Because of the significant moderation of the interaction between *irrelevant cue relation* and *decision relation* by *key association*, I computed two further 2×2 analyses of variance for repeated measurements with the within-subject factors *irrelevant cue relation* (repeated versus changed) and *decision relation* (repeated versus changed) for the percentage of incorrect decisions – one separately for the prime-probe sequences where the keys for the diseases were the same in prime and probe, and one where the keys changed between prime and probe.

The analysis for no key association change sequences showed no significant results (see Figure 8.7a).

The analysis for the key association change sequences revealed a significant interaction between *irrelevant cue relation* and *decision relation*, $F_{(1;62)} = 9.48, p < .01, \eta_p^2 = .13$, showing that the participants decided less correct if they had to change their decision from prime to probe and the irrelevant cue also changed ($M = 21.0\%, SD = 26.6\%$) than if the irrelevant cue was repeated ($M = 13.4\%, SD = 19.2\%$), $t(62) = 2.87, p = .003$.

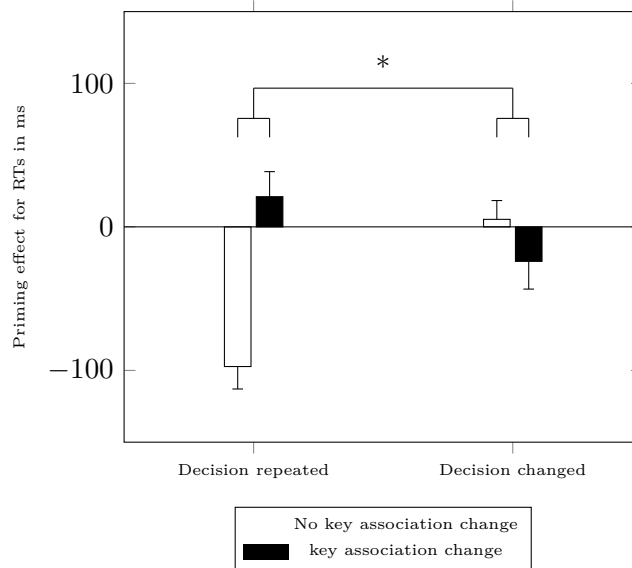


Fig. 8.8. Comparison of the priming effect (irrelevant cue repeated trials minus irrelevant cue changed trials) for trials with no key association change and trials with key association change for reaction times in ms.

On the other hand if the decision had to be repeated and the irrelevant cue was also repeated, less correct decisions were made ($M = 20.7\%$, $SD = 24.7\%$) than if the decision had to be repeated and the irrelevant cue changed ($M = 15.9\%$, $SD = 21.0\%$), $t(62) = 2.56$, $p = .13$. Hence, the analysis revealed the opposite interaction pattern as in the previous experiments (with exception to Experiment 3a; see Section 8.1.2). No further results were significant (see Figure 8.7b).

Furthermore, I computed a $2 \times 2 \times 2$ analysis of variance for repeated measurements with the within-subject factors *irrelevant cue relation* (repeated versus changed), *decision relation* (repeated versus changed), and *key association* (repeated versus changed) for the RTs. The main effect of *irrelevant cue relation* was significant, $F_{(1,62)} = 16.59$, $p < .01$, $\eta_p^2 = .21$, showing that the participants decided faster when the irrelevant cue was repeated ($M = 1121\text{ms}$, $SD = 222\text{ms}$) than if the irrelevant cue changed ($M = 1144\text{ms}$, $SD = 218\text{ms}$). Further, the main effect of *decision relation* was significant,

$F_{(1;62)} = 9.80, p < .01, \eta_p^2 = .14$, showing that the participants decided faster when they had to repeat their decision ($M = 1145\text{ms}, SD = 213\text{ms}$) than if they had to change their decision ($M = 1120\text{ms}, SD = 229\text{ms}$), as well as the main effect of *key association*, $F_{(1;62)} = 82.03, p < .01, \eta_p^2 = .57$, showing that the participants decided faster when there was no change in the key associations ($M = 1089\text{ms}, SD = 201\text{ms}$) as when there was a change ($M = 1176\text{ms}, SD = 242\text{ms}$). Yet, the crucial interaction between *irrelevant cue relation* and *decision relation* again was not significant, $F_{(1;62)} = 1.95, p = .17, \eta_p^2 = .03$. However, again the three-way interaction of *irrelevant cue relation*, *decision relation*, and *key association* reached significance, $F_{(1;62)} = 15.60, p < .01, \eta_p^2 = .20$ (see Figure 8.8). For completeness: a significant interaction of *irrelevant cue relation* and *key association* was also revealed, $F_{(1;62)} = 10.64, p < .01, \eta_p^2 = .15$.

Because of the significant three-way interaction of *irrelevant cue relation*, *decision relation*, and *key association change*, I computed two further 2×2 analyses of variance for repeated measurements with the within-subject factors *irrelevant cue relation* (repeated versus changed) and *decision relation* (repeated versus changed) for RTs— one separately for the prime-probe sequences where the key associations for the diseases were the same in prime and probe, and one where the key association changed between prime and probe.

The analysis for no key association change sequences showed a significant main effect of *irrelevant cue relation*, $F_{(1;62)} = 28.36, p < .001, \eta_p^2 = .31$, showing that participants decided faster when the irrelevant cue was repeated ($M = 1066\text{ms}, SD = 205\text{ms}$) than if it was changed ($M = 1112\text{ms}, SD = 203\text{ms}$), and *decision relation*, $F_{(1;62)} = 7.07, p = .01, \eta_p^2 = .10$, showing that participants decided faster when they had to change their decision ($M = 1112\text{ms}, SD = 203\text{ms}$) than if they had to repeat their decisions ($M = 1076\text{ms}, SD = 216\text{ms}$). Furthermore, the crucial interaction between *irrelevant cue relation* and *decision relation* was significant, $F_{(1;62)} = 19.67, p < .01, \eta_p^2 = .24$, showing that the participants decided faster if they had to change their decision from prime to probe and the irrelevant cue also changed ($M = 1073\text{ms}, SD = 210\text{ms}$) than if the

8. Constraints and Underlying Mechanisms

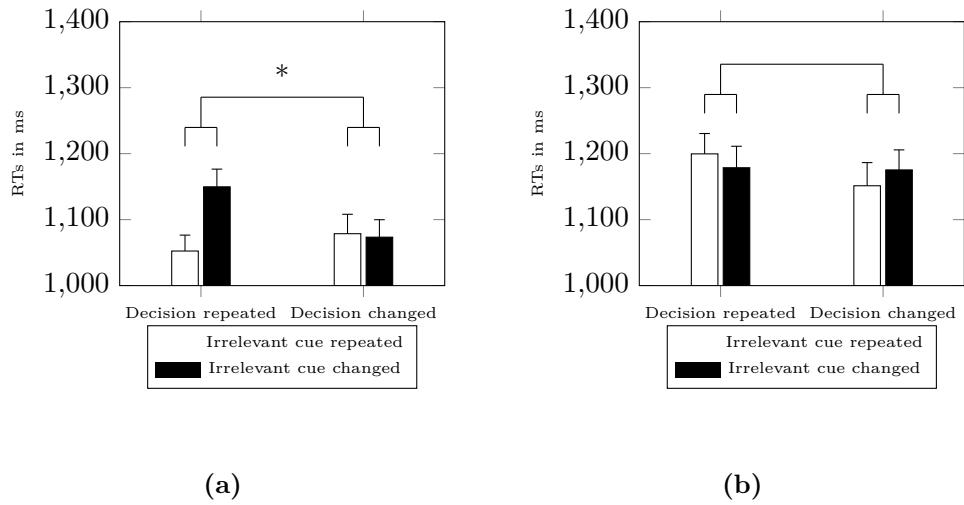


Fig. 8.9. Reaction times in Experiment 3c for trials without key association change (a) and trials with key association change (b).

irrelevant cue was repeated ($M = 1079\text{ms}$, $SD = 234\text{ms}$), $t(62) = .40$, $p = .69$. If the decision had to be repeated and the irrelevant cue was also repeated, decisions were made faster ($M = 1052\text{ms}$, $SD = 191\text{ms}$) than if the decision had to be repeated and the irrelevant cue changed ($M = 1150\text{ms}$, $SD = 213\text{ms}$), $t(62) = -6.22$, $p < .01$ (see Figure 8.9a).

The analysis for the key association change sequences revealed a significant main effect of *decision relation*, $F_{(1;62)} = 5.73$, $p = .02$, $\eta_p^2 = .09$, showing that the participants decided faster when they had to change their decisions from prime to probe ($M = 1163\text{ms}$, $SD = 249\text{ms}$) than if they had to repeat their decision ($M = 1189\text{ms}$, $SD = 242\text{ms}$). However, the expected interaction between *irrelevant cue relation* and *decision relation* was not significant, $F_{(1;62)} = 2.01$, $p = .16$, $\eta_p^2 = .03$. No further results were significant (see Figure 8.9b).

To test if the motor program was bound, I computed two $2 \times 2 \times 2$ analysis of variance for repeated measurements with the within-subject factors irrelevant cue relation (repeated

versus changed), key relation (repeated versus changed)⁴ and decision relation (repeated versus changed) on the number or incorrect decisions and on the RTs.

The first $2 \times 2 \times 2$ ANOVA on the percentage of incorrect decisions showed a significant main effect of *decision relation*, $F_{(1;62)} = 5.31, p = .03, \eta_p^2 = .08$. Furthermore, the interaction between *irrelevant cue relation* and *key relation* was significant $F_{(1;62)} = 11.60, p < .01, \eta_p^2 = .16$, showing that the participants made less incorrect decisions if they had to change the key from prime to probe and the irrelevant cue also changed ($M = 12\%, SD = 16\%$) than if the irrelevant cue was repeated ($M = 15\%, SD = 18\%$), $t(62) = 2.49, p = .02$. If the key was repeated and the irrelevant cue was also repeated, less errors were made ($M = 12\%, SD = 15\%$) than if the key had to be repeated and the irrelevant cue changed ($M = 16\%, SD = 20\%$), $t(62) = -3.20, p < .01$. Furthermore, there also was a significant interaction between *key relation* and *decision relation*, $F_{(1;62)} = 19.90, p < .01, \eta_p^2 = .24$, showing that participants made less errors, if the decision was repeated and the same key had to be pressed ($M = 11\%, SD = 15\%$), than if the decision changed ($M = 17\%, SD = 21\%$), $t(62) = -3.61, p < .01$. On the other hand, if a different key had to be pressed and the same decision was required, participants made more errors ($M = 18\%, SD = 9\%$), than if a different decision was required ($M = 9\%, SD = 13\%$), $t(62) = 4.87, p < .01$. No further results were significant.

A $2 \times 2 \times 2$ ANOVA on the RTs showed a main effect of *irrelevant cue relation*, $F_{(1;62)} = 16.59, p < .01, \eta_p^2 = .21$. This effect was the same as the one reported in the first $2 \times 2 \times 2$ analysis of variance of the RTs above. Also a significant main effect of *decision relation* was found $F_{(1;62)} = 9.80, p < .01, \eta_p^2 = .14$. Furthermore, the interaction of *irrelevant cue relation* and *key relation* was significant, $F_{(1;62)} = 15.60, p < .01, \eta_p^2 = .20$, showing that the participants decided faster if they had to change the key from prime to probe and the irrelevant cue also changed ($M = 1126\text{ms}, SD = 227\text{ms}$) than

⁴The key relation was key changed (KC) if the key that participants had to press to indicate their decision changed from prime to probe and key repeated (KR) otherwise.

if the irrelevant cue was repeated ($M = 1139\text{ms}$, $SD = 233\text{ms}$), $t(62) = 1.12$, $p = .27$. If the key was repeated and the irrelevant cue was also repeated, decisions were made faster ($M = 1102\text{ms}$, $SD = 219\text{ms}$) than if the key had to be repeated and the irrelevant cue changed ($M = 1163\text{ms}$, $SD = 219\text{ms}$), $t(62) = -5.92$, $p < .01$. This relation was significantly modulated by *decision relation*, $F_{(1;62)} = 10.64$, $p < .01$, $\eta_p^2 = .15$, showing that the distractor-response binding effect was larger if the decision had to be repeated ($M = 118\text{ms}$, $SD = 170\text{ms}$), than if the decision changed ($M = 29\text{ms}$, $SD = 196\text{ms}$), $t(62) = 3.62$, $p < .01$. The distractor-response binding effect was calculated as the difference between irrelevant cue repetition effects in key repetition trials and key alternation trials (Moeller & Frings, 2014c). Again, there also was a significant interaction between *key relation* and *decision relation*, $F_{(1;62)} = 82.02$, $p < .01$, $\eta_p^2 = .57$, indicating that participants decided faster, if they had to press the same key, and the decision was also repeated ($M = 1101\text{ms}$, $SD = 193\text{ms}$), than if the decision was changed ($M = 1163\text{ms}$, $SD = 249\text{ms}$), $t(62) = -4.33$, $p < .01$. On the other hand, if a different key had to be pressed and the decision was repeated participants were slower ($M = 1189\text{ms}$, $SD = 242\text{ms}$), than if the decision changed ($M = 1076\text{ms}$, $SD = 216\text{ms}$), $t(62) = 10.64$, $p < .01$. No further results were significant.

8.3.3. Discussion

Experiment 3c could replicate the findings of the previous experiments, i. e., that irrelevant cues are bound in decision tasks. The crucial interaction could be shown for the RTs but not for the number of incorrect decisions, for trials with key association changes a significant interaction opposite to the one that was expected was found. However, this effect could only be found in trials where the key association did not change between prime and probe. Furthermore, the analysis clearly shows that in Experiment 3c the key that was used to indicate the decision was bound. Nonetheless, the analysis cannot directly support the hypothesis that the representation of the decision is bound, as there was no

significant interaction in the expected direction between *decision relation* and *irrelevant cue relation*. There are several possible explanations why no binding of the representation of the decision could be found. First, this test was very conservative, i. e., it is possible that both the key used to indicate the decision as well as the representation of the decision were bound, however the key was bound much stronger. In that case the binding of the key could have overruled the binding of the decision, making it undetectable. This hypothesis is supported by the three way interaction in the RTs that was found for the analysis of the bindings of the motor program. The three way interaction indicates that the decision was bound. However, as shown by the significant three-way interaction the resulting binding included the irrelevant cue, the motor program and the decision. One hypothesis for this could be that a decision is only retrieved, if it ultimately leads to the same or a similar action. The hypothesis that decisions are actually bound, is further supported by the bindings between decision relation and key relation found both for the number of incorrect decisions as well as for RTs. Second, the analysis also shows that trials in which the association changed were much harder for the participants, i. e., error rates doubled approximately. This increased difficulty in the trials with key association changes may also have prohibited binding of the decision representation and instead have favored low level associations, such as the key used to indicate the decision. Further, experiments should try to fully prohibit binding of response codes, e. g., by changing the response modality. Both explanations should, however, be considered post-hoc explanations and hence require experimental evaluation.

8.4. Experiment 3d

Since Experiment 3c did not clearly confirm the hypothesis that the mental representation and not only the key press used to indicate the decision is bound, I wanted to investigate if other decision parameters are influenced by binding processes. Hence, in Experiment 3d, I tested whether confidence ratings are influenced in the same way as the decision behavior. Specifically, participants should be more confident in their repeated decision if the irrelevant cue was repeated in the probe than if the irrelevant cue was changed. However, they should be more confident in their changed decision when the irrelevant cue also changed than if it was repeated. So, Experiment 3d was designed to investigate if distractor-response binding in decision making also influences the subjective feeling of confidence and not only the actual decision behavior.

As Glöckner (2010) have shown, our ability to make decisions can be modeled on the basis of Gestalt processes. For example, subjective validities of cues are changed during the decision process, so that the validities of cues not fitting the overall Gestalt are reduced, while validities of cues which fit well are increased (Glöckner et al., 2008). Likewise, decision times can be predicted by the coherence of the cues, but not by the overall number of cues. Thus, participants were slower on trials where cues were removed to decrease coherence. If cues were removed to increase coherence, however, participants were faster (Glöckner & Betsch, 2012). One mechanism that may be assumed, is that the information retrieved through repeated irrelevant cues also takes part in the same Gestalt process. For example, Giesen and Rothermund (2014) have shown that repeating distractors not only retrieves the response, but also the target (*distractor-target bindings*). Similarly one could assume that repeating irrelevant cues will retrieve the previous relevant cue, which then takes part in the consistency maximization strategy. Since including a relevant cue, which goes against the decision indicated by the current relevant cue (ICR-DC Trials), decreases coherence, this would predict higher times needed for the decision as well as more errors. Similarly, retrieving a relevant cue through a repeated

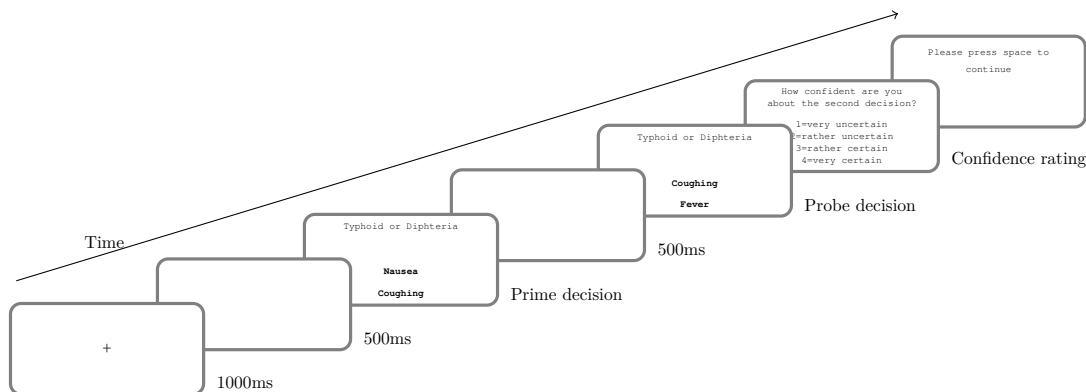


Fig. 8.10. The sequence of events of one trial in Experiment 3d. Stimuli are not drawn to scale.

irrelevant cue, which is coherent with the currently presented relevant cue, would cause perception of the Gestalt to be easier, leading to faster decision times and less errors. Moreover, if the relevant cue from the previous decision is retrieved, this should increase the general support of the Gestalt, leading to higher confidence in the decision. This Experiment 3d tests if the confidence in the decision is similarly influenced as reaction times and the number of errors.

8.4.1. Methods

Participants. Further, thirty-one students (28 females) from the University of Trier participated in Experiment 3d. They received partial course credit for their participation. The median age of all participants was 22 (ranging from 18 to 77 years). All participants had normal or corrected-to-normal vision.

Materials. The materials and procedure were the same like in Experiment 2a (see 7.2) with the following exception (see Figure 8.10): after every probe a display followed that asked “How confident are you about the second decision?”⁵ Thus, the participants had to rate their confidence in their last decision. They had to indicate

⁵This question was written in German. The original wording was “Wie sicher fühlst du dich bei dieser zweiten Entscheidung?”

their answer via a key press of one number between 1 (1 meaning low confidence and 4 meaning high confidence).

Design. The design comprised three within-subject factors, namely *irrelevant cue relation* (repeated versus changed), *decision relation* (repeated versus changed), and the *validity strength* of the relevant cue in the probe ($v = .80$ versus $v = .60$). The factors were fully balanced, i.e. all possible combinations of factors were presented eight times. There also were 68 additional trials which did not follow the sequential priming pattern to avoid the recognition of a pattern by the participants. These trials were not included in the analyses. In all trials included in the later analysis the relevant cue was always changed between prime and probe. At the same time the validity was always changed between prime and probe. Hence, for a probe with $v = .80$ the prime would indicate a response with a likelihood of $v = .60$ and vice versa.

8.4.2. Results

I calculated and cleaned the distribution of RTs in the same way as for Experiment 1a. Therefore, 33% of all RTs were discarded (first 30% were discarded because of prime errors, then 3% of the remaining trials were discarded because the RTs were outside of the fences, see Tukey, 1977). After cleaning of the data, one further participant had to be excluded from the analysis of the RTs due to insufficient data. I also analyzed the numbers of incorrect decisions in the same fashion as in Experiment 1a. For the analysis of error rates only trials with correct decisions to the prime presentation were considered, i.e. 30% of all trials were discarded. Mean RTs, error rates, and confidence ratings are depicted in Table 8.4.

Separate analyses for the confidence ratings, RTs and number of incorrect decisions were computed. Furthermore, Pillai's trace was taken as a criterion for all variance analyses of repeated measurements.

Tab. 8.4. Reaction times, error rates, and confidence ratings for Experiment 3d

	Decision Relation			
	Decision repetition		Decision change	
<i>v</i> = .60 condition				
Reaction times (ms)				
IRC repetition	1059	(428)	1068	(480)
IRC change	1038	(379)	1010	(419)
PE	23	(237)	54	(278)
Error rates (%)				
IRC repetition	26	(29)	31	(28)
IRC change	39	(33)	24	(25)
PE	-13	(38)	7	(26)
Confidence ratings				
IRC repetition	2	(1)	2	(1)
IRC change	2	(1)	2	(1)
PE	0	(0)	0	(1)
<i>v</i> = .80 condition				
Reaction times (ms)				
IRC repetition	1051	(426)	1001	(341)
IRC change	1082	(419)	1077	(444)
PE	-31	(303)	-77	(313)
Error rates (%)				
IRC repetition	29	(30)	25	(26)
IRC change	34	(35)	20	(25)
PE	-5	(28)	5	(25)
Confidence ratings				
IRC repetition	2	(1)	2	(1)
IRC change	2	(1)	2	(1)
PE	0	(1)	0	(1)

8. Constraints and Underlying Mechanisms

To test if the confidence in a decision was influenced by the distractor-response binding effect, I computed a $2 \times 2 \times 2$ ANOVA of the rating of confidence in the probe decision with the within-subject factors *irrelevant cue relation* (repeated versus changed), *decision relation* (repeated versus changed), and *validity strength* ($v = .80$ versus $v = .60$). This analysis showed no significant effect^{6 7}.

I performed a $2 \times 2 \times 2$ ANOVA of the percentage of incorrect decisions with the factors *irrelevant cue relation* (repeated versus changed), *decision relation* (repeated versus changed), and *validity strength* ($v = .80$ versus $v = .60$). The analysis revealed the expected significant interaction of *irrelevant cue relation* and *decision relation*, $F_{(1;30)} = 6.33, p = .02, \eta_p^2 = .17$, indicating that the participants decided less incorrect if they had to change their decision from prime to probe and the irrelevant cue also changed ($M = 4.2\%, SD = 11.3\%$) than if the irrelevant cue was repeated ($M = 6.6\%, SD = 11.5\%$), $t(29) = 2.25, p = .03$. If the decision had to be repeated and the irrelevant cue was also repeated, fewer incorrect decisions were made ($M = 6.0\%, SD = 12.3\%$) than if the decision had to be repeated and the irrelevant cue changed ($M = 8.3\%, SD = 16.6\%$),

⁶Assuming that people differ in their confidence if they decided in line with the indicating relevant cue or against it, I computed the same analysis only for probes where the participants decided in line with the relevant cue. However, this analysis only showed a significant main effect of *decision relation*, $F_{(1;25)} = 6.00, p = .02, \eta_p^2 = .19$, indicating that participants rated their confidence in their decision higher when they repeated their decision ($M = 2.5, SD = .8$) than if they changed it ($M = 2.4, SD = .7$).

⁷To test if the confidence measurement worked at all, I also separated all trials into high confidence trials (rating higher than two) and low confidence trials (rating lower or equal to two). A $2 \times 2 \times 2$ analysis of variance for repeated measurements for the percentage of incorrect decisions with the factors *irrelevant cue relation* (repeated versus changed), *decision relation* (repeated versus changed), *validity strength* ($v = .60$ versus $v = .80$), and *confidence level* (low versus high), revealed a main effect of *confidence level*, showing that participants made more incorrect decisions in trials with low confidence ($M = 36\%, SD = 23\%$) than in trials with high confidence ratings ($M = 18\%, SD = 19\%$). No further results were significant.

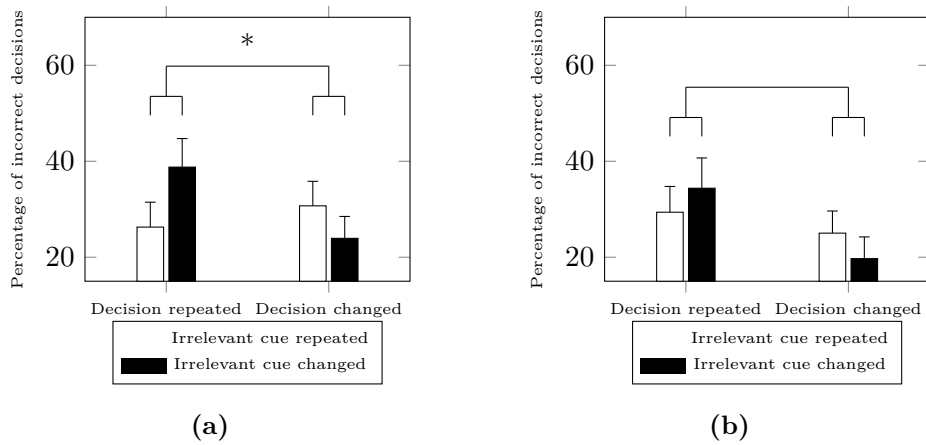


Fig. 8.11. Percentage of incorrect decisions in Experiment 3d for trials with probes with $v = 0.60$ (a) and trials with probes with $v = 0.80$ (b)

$t(29) = -1.22, p = .21$. This interaction was not modulated by the *validity strength*, $F_{(1;30)} = .91, p = .35, \eta_p^2 = .03$. No further results were significant.

For completeness, I computed two further 2×2 analyses of variance for repeated measurements with the within-subject factors *irrelevant cue relation* (repeated versus changed) and *decision relation* (repeated versus changed) for the percentage of incorrect decisions.

The 2×2 ANOVA with the factors *irrelevant cue relation* (repeated versus changed) and *decision relation* (repeated versus changed) exclusively on the trials with probes of a $v = .60$ for the percentage of incorrect decisions revealed no main effect of *irrelevant cue relation* or *decision relation*. However, the expected interaction between *irrelevant cue relation* and *decision relation* was significant, $F_{(1;30)} = 5.73, p = .02, \eta_p^2 = .16$, indicating that the participants decided less incorrect if they had to change their decision from prime to probe and the irrelevant cue also changed ($M = 23.9\%, SD = 25.4\%$) than if the irrelevant cue was repeated ($M = 30.7\%, SD = 28.5\%$), $t(30) = 3.94, p < .001$. If the decision had to be repeated and the irrelevant cue was also repeated, fewer incorrect decisions were made ($M = 26.3\%, SD = 28.9\%$) than if the decision had to be repeated

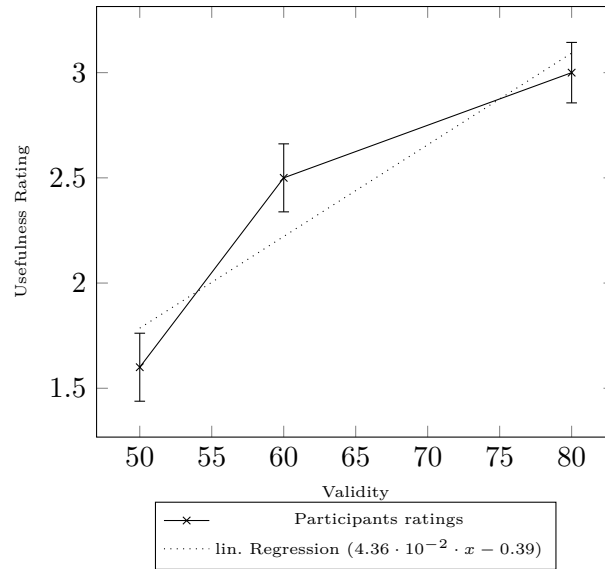


Fig. 8.12. Participant's usefulness ratings of the cues for Experiment 3d.

and the irrelevant cue changed ($M = 38.8\%$, $SD = 33.1\%$), $t(30) = 0.10$, $p = .34$ (see Figure 8.11a).

Furthermore, the second 2×2 analysis of variance for repeated measurements with the within-subject factors *irrelevant cue relation* (repeated versus changed) and *decision relation* (repeated versus changed) for the percentage of incorrect choices in trials with probes of a $v = .80$ revealed no significant main effect of *irrelevant cue relation*, but a significant main effect of the *decision relation*, $F_{(1;30)} = 4.10$, $p = .05$, $\eta_p^2 = .12$, showing that participants made more incorrect decisions if they had to repeat their decision ($M = 31.9\%$, $SD = 29.4\%$) than if they had to change their decision ($M = 22.4\%$, $SD = 22.1\%$). However, the crucial interaction between *irrelevant cue relation* and *decision relation* was not significant, $F_{(1;30)} = 1.00$, $p < .15$, $\eta_p^2 = .07$ (see Figure 8.11b).

A $2 \times 2 \times 2$ repeated measurement analysis of variance for repeated measurements with the within-subject factors *irrelevant cue relation* (repeated versus changed), *decision relation* (repeated versus changed) and *validity strength* ($v = .80$ versus $v = .60$) of the RTs showed no significant results. No further analyses for RTs were calculated.

The rating how useful the cue was for all decisions, which participants had performed at the end of the Experiment 3d, showed that the participants rated the irrelevant cues as the most useless ($M = 1.6, SD = .9$) and they rated the cues with a validity of $v = .60$ ($M = 2.5, SD = .9$) lower than if they had a validity of $v = .80$ ($M = 3.0, SD = .8$). This difference was significant, $F_{(2;29)} = 24.90, p < .01, \eta_p^2 = .63$ (see Figure 8.12).

8.4.3. Discussion

Experiment 3d could again replicate a binding effect of irrelevant cues and decisions in the percentage of incorrect decisions. However, no distractor-response binding effect could be shown for the RTs or confidence ratings in the probe decisions. Furthermore, no main effect of validity for the confidence ratings could be shown. This indicates that the operationalization of the confidence ratings has failed. Although participants were more likely to make an error when they gave a low confidence rating, one would also expect confidence ratings to be dependent on the learned cue validities. That no such influence could be found, indicates that participant's rating did not conform to the concept of confidence that was expected here. Furthermore, not all participants assigned low usefulness ratings to irrelevant cues. A visual inspection of the usefulness ratings revealed that close to half of the participants seem to have entered fixed patterns (e. g., fours on all cues). In combination with the high number of error rates in the prime trials, this indicates a lack of motivation of the participants for Experiment 3d. However, because of the high number of uncooperative participants the data could not be cleaned further.

Part III.

General Discussion and Conclusions

9. General Disussion

9.1. Summary

Generally, the main goal of this thesis was to test if distractor-response binding also affects decision making. Therefore, the distractor-to-distractor priming paradigm (Frings et al., 2007) was first adapted to a decision task without uncertainty and later for decision making under uncertainty.

In the following section (9.1.1) I start with a summary of the hypotheses of this thesis. In the next section (9.1.2) I will present a concise summary of the experimental results. After that I discuss the implications for these results in context of perception and action control and decision making. I end the thesis with a conclusion and an outlook.

9.1.1. Hypotheses

I hypothesized that distractor-response binding also influences decision making under certainty as well as under uncertainty. Distractor based retrieval of event files has been shown to be very stable. In particular, it occurred in different paradigms of visual (Frings & Rothermund, 2011; Frings et al., 2007; Hommel, 1998; Rothermund et al., 2005), auditive (Leboe et al., 2006; Mayr & Buchner, 2006; Mayr et al., 2009; Moeller et al., 2012; Zmigrod & Hommel, 2009), tactile (Moeller & Frings, 2011; Zmigrod et al., 2009), and crossmodal (Frings, Moeller, & Rothermund, 2013; Zmigrod et al., 2009) tasks. For example, it was demonstrated that actions were influenced by response retrieval due to distractor repetition for simple letter identification tasks, word categorization, and

responses to stimulus locations (e. g., Frings & Moeller, 2010; Frings & Rothermund, 2011; Giesen & Rothermund, 2011). Regarding the robustness of distractor-response binding it seems to be plausible that not only actions – or more precisely action goals – are influenced but also other cognitive representations like decisions (e. g., Hommel, 2009). Therefore, in nine experiments I tested if decisions are influenced by distractor-response binding. First, I assumed that distractor-response binding affects decision making in deterministic contexts. In a next step, I hypothesized that even decision making under uncertainty is influenced by distractor based retrieval processes. Further, I tried to challenge the results that distractor-response binding is present in decision making under certainty as well as under uncertainty, e. g., by testing if it is subject to the same constraints as distractor-response binding in action and perception. Thus, I assumed that the distractor-response binding will last even when the second decision situation does not follow immediately after the first decision situation. Furthermore, I expected the same mechanism of the distractor-response binding in actions in the area of decision making. Therefore, I assumed that only irrelevant cues are bound which are semantically related to the relevant cue. In action control it has been shown that distractor-response binding is modulated by semantic relation (Giesen & Rothermund, 2011), so I expected the same relation for decision making. Moreover, I hypothesized that distractor-response binding in decision making is an automatic process like in action control (Hommel, 2005; Hommel & Colzato, 2004, 2009) and therefore cannot be suppressed even if the cognitive resources for the decision task are not limited by the experimental task. Another hypothesis that was used to challenge the previous findings was that the actual decision is bound in an event file, i. e., the decision is bound independently of the key press used to indicate the decision. The final hypothesis was that not only decisions can be bound in an event file but even the feeling of confidence in the decision.

Tab. 9.1. Summary of the interactions for all Experiments

Experiment	Results		
	RTs	Incorrect Decisions	Confidence Ratings
Exp. 1a	$F_{(1;14)} = 4.44, p = .05, \eta_p^2 = .24^a$	$F_{(1;14)} = .90, p = .36, \eta_p^2 = .06$	
Exp. 1b	$F_{(1;34)} = 4.41, p = .04, \eta_p^2 = .12$	$F_{(1;34)} = .96, p = .33, \eta_p^2 = .03$	
Exp. 1c	$F_{(1;34)} = 3.47, p = .07, \eta_p^2 = .09$	$F_{(1;34)} = .43, p = .52, \eta_p^2 = .01$	
Exp. 2a	$F_{(1;30)} = .66, p = .29, \eta_p^2 = .04$	$F_{(1;30)} = 19.15, p < .01, \eta_p^2 = .39$	
Exp. 2b	$F_{(1;65)} = 47.92, p < .01, \eta_p^2 = .42$	$F_{(1;65)} = 5.59, p = .02, \eta_p^2 = .08$	
Exp. 3a ^b	$F_{(1;33)} = 4.48, p = .04, \eta_p^2 = .12^c$	$F_{(1;33)} = 1.93, p = .18, \eta_p^2 = .06$	
Exp. 3b	$F_{(1;29)} = .08, p = .79, \eta_p^2 < .01$	$F_{(1;29)} = 2.45, p = .24, \eta_p^2 = .05$	
Exp. 3c	$F_{(1;62)} = 1.95, p = .17, \eta_p^2 = .03$	$F_{(1;62)} = 1.95, p = .17, \eta_p^2 = .03$	
Exp. 3d	$F_{(1;29)} < .01, p = .95, \eta_p^2 < .01^d$	$F_{(1;30)} = 6.33, p = .02, \eta_p^2 = .17$	$F_{(1;30)} = .01, p = .91, \eta_p^2 < .01$

^a Only the DR trials showed a significant difference whereas DC trials were descriptively in the opposite direction as hypothesized.

^b No significant interaction was expected in this experiment.

^c The interaction showed the opposite pattern than expected (see Section 8.1.2 and 8.1.3).

^d One participant had to be excluded because of insufficient data after cleaning of reaction times.

9.1.2. Experiments and Results

I conducted nine experiments to test these hypotheses. The complete main results (interactions of decision relation with irrelevant cue relation) of all experiments are shown in Table 9.1. In all nine experiments the two factors irrelevant cue relation (repeated versus changed) and decision relation (repeated versus changed) were varied orthogonally. Thus, distractor-response binding was expressed statistically as an interaction of irrelevant cue relation and decision relation. The experiments were divided in three blocks.

In the first block of experiments (Chapter 6) I conducted three experiments to demonstrate that distractor-response binding is present in deterministic decision making. In all three experiments participants had the role of a doctor who had to decide if a patient had the disease at question or not based on two symptoms. Of the two symptoms one was relevant and one was irrelevant. The relevant cue was unambiguously associated to a disease, i. e., if the patient had the associated symptom and the diagnosis had to be made about the compatible disease, the patient always had the disease. I could repeatedly show that distractor-response binding influenced the reaction times of decision-makers under certainty (Experiments 1a and 1b). In Experiment 1c the analysis did not indicate

an influence of distractor-response binding on the reaction times. In this experiment, filler decision tasks, i. e., tasks not following the sequential priming paradigm, which were interspersed between prime and probe were presented, to test if the bypass rule (Krueger & Shapiro, 1981; see also Fletcher & Rabbitt, 1978; Smith, 1968) could also explain the findings of the previous experiments. I found no significant interaction in this experiment, indicating that the bypass rule may also account for the previous findings. However, the effect size was about the same as in the previous experiment. Since the previous experiments had just barely enough power to detect the effects, the missing interaction effect of Experiment 1c could also be explained by insufficient power. Hence, the result of this experiment is inconclusive and both distractor-response binding as well as the bypass rule could account for my findings (see Section 6.3.3, however, for a possible link between the bypass rule and distractor-response binding). Experiment 1a showed a medium to large effect whereas experiments 1b and 1c only showed a small effect (effect sizes according to Cohen, 1988). Previous studies of distractor-response binding indicated a large (Frings, Larra, et al., 2013; Frings, Moeller, & Rothermund, 2013; Moeller & Frings, 2011; Moeller et al., 2012) or medium effect size (Frings & Moeller, 2012; Giesen, Frings, & Rothermund, 2012), $.14 \leq \eta_p^2 \leq .80$. Due to the general differences in task settings and distractor modality within these experiments and the ones reported here, a comprehensive comparison is not possible. However, at a first glance, the results show that the effect sizes found for Experiment 1a were in the range of previous findings, while the results for experiments 1b and 1c are somewhat smaller. One reason for the difference between the effect sizes in Experiment 1a and the other two experiments of this block, may be that the confound were reduced in the later experiments. However, as a between experiment interpretation, this hypotheses would require experimental validation. Still, as a significant interaction was found in Experiment 1b, even the effects of Experiment 1a may not be fully explainable by the confound alone. None of the experiments with deterministic decisions showed a significant interaction of decision relation and irrelevant

cue relation in the error rates. Again this finding is in line with previous research, in which the influence of distractor-response binding on the error rates generally showed no effect (Frings & Moeller, 2012) or a smaller effect (Frings, Moeller, & Rothermund, 2013; Giesen et al., 2012; Moeller et al., 2012)¹.

In the second block of experiments (Chapter 7), I adapted the paradigm to decision situations under uncertainty. Now the participants had to say which of two diseases a patient had. Again, the patient named two symptoms. One was strongly ($v = .80$) or moderately ($v = .60$) associated with one of the two diseases (the relevant cue) whereas the other one did not differentiate between the two diseases (the irrelevant cue). In the first experiment of this block, I varied the validity of the relevant cue as a within-subject factor. Thus, if the relevant cue in the prime had a validity of $v = .60$ the relevant cue in the following probe had a validity of $v = .80$ and vice versa. In the second experiment of this block the same paradigm was used but now the validity of the relevant cue was realized as a between-subject factor. In both experiments of this block I found an influence of distractor-response binding on the percentage of incorrect decisions. In Experiment 2b I also found an influence of distractor-response binding on the RTs. A closer analysis of the validity strength showed that in Experiment 2b the number of incorrect decisions was only influenced in the condition with $v = .80$, whereas in Experiment 2a there was a significant interaction for both conditions. In Experiment 2b the distractor-response binding effect on the RTs was similar for both $v = .80$ and $v = .60$ (no significant three-way interaction). The overall effects in this block were large (error rates in Experiment 2a and RTs in Experiment 2b) to small (error rates in Experiment 2b, see Table 9.1). Therefore, Experiment 2a and Experiment 2b clearly demonstrate the presence of distractor-response binding in decision making under uncertainty.

¹In the previous studies used for comparison, only Moeller and Frings (2011) found a larger effect on error rates than on RTs. Frings, Larra, et al. (2013) did not report analyses of the error rates.

In the third block of experiments (Chapter 8) I investigated possible constraints of distractor-response binding in decision making under uncertainty. Thus, in Experiment 3a I used the same paradigm as in Experiment 2a but I changed the irrelevant cue from a symptom to the day of the patient's visit. As expected no distractor-response binding occurred and the comparison with Experiment 2a showed a significant difference between the interaction of irrelevant cue relation and decision relation in these two experiments. Therefore, I conclude that the irrelevant cue has to be semantically related to the relevant to be bound in an event file. This is also the case for distractor-response binding in action control (Giesen & Rothermund, 2011). In Experiment 3b again I used the paradigm from Experiment 2a, but here I removed the instruction that the participants had to respond as fast as possible. Thus in Experiment 3b, the participants could take all their time they needed for the decisions. Distractor-response binding had an influence on the percentage of incorrect decisions but only for the probes with a validity of $v = .80$. A comparison with Experiment 2a showed that the strength of the interaction was significantly reduced. Under the theoretical assumption that event files are part of the mechanism of routinized decision making or automatization, this is in line with Betsch et al. (2004), who also found that the amount of routine relapse errors is modulated by time pressure. The RTs were not influenced significantly by distractor-response binding. In the third experiment of this block I used the material and design of the condition with the relevant cue with a validity of $v = .80$ of Experiment 2b. However, for Experiment 3c the participants were not directly instructed which key they had to press for each of the diseases, but rather a label indicated which key c indicated which disease in each trial. Therefore, there were prime-probe sequences where the association between key and diseases remained and other in which it changed. I found distractor-response binding in the prime-probe sequences where the association remained but not in the prime-probe sequences where it changed. In trials where the key association remained, the influence of distractor-response binding was revealed for the RTs but not for the percentage of incorrect decisions. For trials in which

the key association changed a significant effect of the irrelevant cue relation was found for the percentage of incorrect decisions, but not for the RTs. However, the interaction was in the opposite direction as expected from distractor-response binding. In the analysis I found significant evidence that the motor program for the key was bound. This effect was found both in the RTs as well as in the number of incorrect decisions. There are several interpretations possible. First, it is possible that the decision can only be bound in connection with the association of the related action. This idea is supported by a three way interaction between the key relation, decision relation, and irrelevant cue relation, indicating that the binding between motor program and irrelevant cue was modulated by the decision. This finding is also in line, with the idea that bindings of decisions are part of routine building processes which are based on visuomotor integration and not on visual integration (see Section 2.3). The bindings between the motor programs and irrelevant cues are most likely produced by a process similar to visuomotor integration, so the three-way interaction indicates that decisions are bound by the same mechanism. Another interpretation could be that the higher complexity of the task may have prohibited bindings of the decision, however, this would not explain the significant interactions with decision relation. Still, as these hypotheses were only constructed post-hoc, this experiment should be considered inconclusive and further experimental evaluation is clearly needed.

In the last experiment I used again the material of Experiment 2a. In Experiment 3d I added the question “How confident are you about the second decision?” after the probe. Furthermore, as another manipulation check, at the end of the Experiment 3d the participants had to indicate how useful they rated the different cues. The feeling of confidence after the probe was neither influenced by the strength of the validity nor the distractor-response binding. However, distractor-response binding was revealed in the percentage of incorrect decisions (for the relevant cues with a validity of $v = .60$) but not in the RTs. One possible conclusion could be that the confidence is not influenced by

SR bindings. However, as not even a main effect of the cue validity in the probe on the confidence rating was found, it seems more likely that the operationalization attempted in this experiment failed. The usefulness ratings, however, showed that participants had clearly learned the cue validities, as less valid cues were rated less useful. Since there was a significant distractor-response binding effect for probes with a validity of $v = .60$ this also indicates that knowledge about the usefulness of a cue does not prevent that cue from being integrated in an event file.

From the combined results of these nine Experiments I conclude that distractor-response binding plays a role in decision making under certainty as well as under uncertainty. Therefore, the theory of event coding should be considered in the realm of decision making. In the following section I will show implications of these results for action and perception (Section 9.2.1) and for decision making (Section 9.2.2). First, though, I will give a short overview of the role of the manipulation of cue validity.

The role of validity can be seen in Table 9.2. However, this table does not allow a clear interpretation. One hypothesis one could assume, would be that stronger validities in the prime lead to stronger bindings. However, no such effect could be found. In Experiment 2a the distractor-response binding effect was descriptively larger in the trials with primes with a validity of $v = .60$, in Experiment 2b the opposite relationship was found. Neither of these experiments showed a significant influence of the validity. The other experiments showed similar inconclusive results. This indicates that validity does not play a role. A decision is just as strongly influenced if the decision-maker knows quite well what should be the correct solution, as if he knows only little. This is quite surprising, since in order to use event files for routine building, it appears to be helpful to also include knowledge about how sure one was in the previous decision (at least if no further feedback is presented). If one is not sure, that the decision is correct, including this decision in a routine could later prove maladaptive. However, the lack of any replicable significant interactions between

Tab. 9.2. Summary for the interactions for probes with $v = .60$ and probes with $v = .80$ across all experiments.

Experiment	Results		
	RTs	Incorrect Decisions	Confidence Ratings
Exp. 2a			
$v = .60$	$F_{(1;30)} = 3.45, p = .07, \eta_p^2 = .10$	$F_{(1;30)} = 7.84, p < .01, \eta_p^2 = .21$	
$v = .80$	$F_{(1;30)} = .97, p = .76, \eta_p^2 < .01$	$F_{(1;30)} = 21.21, p < .01, \eta_p^2 = .41$	
Exp. 2b ^a			
$v = .60$	$F_{(1;31)} = 9.20, p < .01, \eta_p^2 = .23$	$F_{(1;31)} = 2.16, p = .15, \eta_p^2 = .07$	
$v = .80$	$F_{(1;34)} = 47.53, p < .01, \eta_p^2 = .58$	$F_{(1;34)} = 4.17, p = .05, \eta_p^2 = .11$	
Exp. 3a ^b			
$v = .60$	$F_{(1;33)} = 5.42, p = .03, \eta_p^2 = .14^c$	$F_{(1;33)} = 1.72, p = .20, \eta_p^2 = .05$	
$v = .80$	$F_{(1;33)} = .51, p = .48, \eta_p^2 = .02$	$F_{(1;33)} = .38, p = .54, \eta_p^2 = .01$	
Exp. 3b			
$v = .60$	$F_{(1;29)} = .03, p = .87, \eta_p^2 < .01$	$F_{(1;29)} = .03, p = .86, \eta_p^2 = .01$	
$v = .80$	$F_{(1;29)} = .07, p = .82, \eta_p^2 < .01$	$F_{(1;29)} = 4.77, p = .04, \eta_p^2 = .14$	
Exp. 3d			
$v = .60$	$F_{(1;30)} = .29, p = .59, \eta_p^2 = .01$	$F_{(1;30)} = 5.73, p = .02, \eta_p^2 = .16$	$F_{(1;30)} = .40, p = .53, \eta_p^2 = .01$
$v = .80$	$F_{(1;29)} = .24, p = .63, \eta_p^2 < .01^d$	$F_{(1;30)} = 1.00, p = .15, \eta_p^2 = .07$	$F_{(1;30)} = .58, p = .45, \eta_p^2 = .02$

^a In this experiment probes of $v = .60$ were combined with primes of $v = .60$ and probes of $v = .80$ with primes $v = .80$.

^b No significant interaction was expected in this experiment.

^c The interaction showed the opposite pattern as expected (see Section 8.1.2 and 8.1.3).

^d One participant had to be excluded because of insufficient data after cleaning of reaction times.

validity and distractor-response binding effects indicates that bindings are constructed without regard to the validity, so that maladaptive learning may arise.

9.2. Implications

In the following sections I present the implications from the mentioned results for the realm of perception and action control as well as for the realm of decision making.

9.2.1. Implications for Perception and Action Control

The Experiments in Part II indicate similarities between basic attentional processes and decision making processes. There are multiple ways to interpret these similarities and incorporate them into the existing theory.

As a first explanation for the findings, one might assume that mechanisms, which are similar in structure, are used for decision making and for object perception and action. In this interpretation, object perception and action would produce an event file, while making a decision can lead to the construction of a *decision file*. In this decision file, the cues that are used and the resulting decision are incorporated and bound together for later reuse. One reason could be that the brain tries to store previous decisions for later reuse, so that costly inferences do not have to be drawn every time. The idea here is similar to the reasoning that was used in the instance theory of automaticity (Logan, 1988) or the exemplar model (Medin & Schaffer, 1978). In the same way as described by the instance theory of automaticity, a decision that is often repeated can become a automatic routine (James, 1890/2014), once the stored instances frequently outrace the algorithm that is used for inferences. In day-to-day life we do not want to make the same decisions over and over again, instead we just want to repeat fixed learned routines. These routines have been shown to be stable even under changing environments (e. g., Betsch et al., 2002, 2004; Bröder et al., 2013). Again like in the area of action control (see Section

2.1), this requires binding between the presented cues and the result of the decision. It is unlikely that these bindings are only produced when the information is transferred to long-term memory, but rather that these bindings are produced in the same obligatory fashion as the bindings in the instance theory of automaticity (Logan, 1988). Furthermore, effects of routines, e. g., routine relapses, seem to be stronger under time pressure (Betsch et al., 2004), which indicates that they are used as a part of decision automatization. One important difference between the routines discussed in Betsch et al. (2004) and the findings here, however, is that these routines are produced through direct feedback in a large number of trials (Betsch et al., 2004, used 24 maze problems in Experiment 1 and 32 maze problems in Experiment 2), whereas in the experiments here the effect is caused by a single preceding trial, to which no feedback was given. The empirical evidence from the current experiments indicates that the role of feedback and mere repetition should require further investigation. For example, a further experiment building on the one presented by Betsch et al. (2004) could manipulate the routine strength by introducing a number of trials without feedback between routine formation and routine recall (i. e., the test with a changed environment). If feedback is not required to strengthen routines, the number of relapse errors should increase with the number of repetitions.

However, the findings presented here, do not only indicate that relevant information is included in this kind of decision file, but irrelevant cues are included as well. Furthermore, the experiments show that previously established routines can be broken by irrelevant information from the previous trial. In all experiments routines were established through a large number of practice trials with feedback. However, in DR-RC trials, the participants decided not in accordance with the previously established routine. In this case the decision was frequently repeated although the routine would indicate a decision change. A possible explanation is that decision files stored in working memory could override the previously established routine, which is based on instances that have to be retrieved from long-term memory.

An alternative explanation for the findings would be that the results of decisions are stored together with perception and action features in event files. In many cases, e. g., in case of the experiments presented here, but also in the case of a city size task, the results of a decision are derived features of an object. A general mechanism of object perception requires a theory, which includes integration of features from different sources. A dog can both be recognized either from a picture, but also from the barking or even from a description. Quiroga et al. (2005) found highly specific neurons, which in their trials only responded to certain persons or objects, e. g., Bill Clinton or Jenifer Aniston². However, these cells did not only respond to pictures of the persons, but also to their names, indicating high level semantic representations, which could be triggered through many different modalities. The stability of stimulus-response and distractor-response binding across modalities (Frings, Moeller, & Rothermund, 2013; Zmigrod et al., 2009), with different presentation formats (Horner & Henson, 2011) or for different presentations of the same object (Denkinger & Koutstaal, 2009; Schnyer et al., 2007) also indicates that the features which are processed and bound are not visual in nature, but rather high-level semantic features. Under the assumption that the results of decisions are bound in the same way as any other stimulus or response feature, this would mean that inference mechanisms used in decisions are just another pathway through which high level features can be activated. From an ecological perspective including the results of decisions seems sensible. Why should I represent, for example, the size of a city differently, if it was told to me, than if I inferred it from other cues? Or put differently, which purpose would a

²This should not be seen as evidence that these cells are some kind of grandmother cell. Instead these neurons or groups of neurons should be seen as arrays encoding very specific configurations of other features that are only exhibited by a few, maybe even only a single person (Quiroga, Kreiman, Koch, & Fried, 2008). This basically means these cells should be considered features and not object representations.

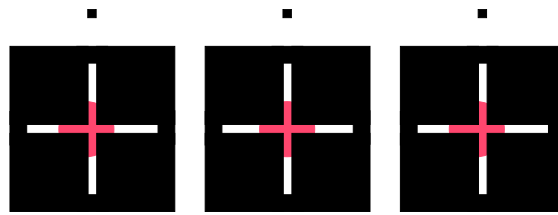


Fig. 9.1. A stereoscopic version of the Ehrenstein configuration. If these images are viewed with crossed eyes, in the resulting image from the left and middle image a red disc in front of a white cross can be perceived. The boundaries of the disc expand into the black region. In the image resulting from the right and middle image, a black shape with a cross-shaped hole in front of a red disk can be seen. There is no perceived transparency in this case. If the images are viewed with uncrossed eyes, the roles of the images are reversed (Nakayama, Shimojo, & Ramachandran, 1990, p. 500).

dual representation of the same facts as results of decisions and as results of perception serve?

The idea to see inference as an inherent part of perception is not new. Rock (1983) developed a theory of perception, in which, for example, context effects such as the Müller-Lyer Illusion (e. g., Wirtz, Häcker, & Stapf, 2013) are used, to reason that certain stimuli can only be interpreted in relation to other simultaneous stimuli. Another example is the stereoscopic version of the Ehrenstein configuration (e. g., Dresch-Langley, 2009), as presented in Figure 9.1. When viewing this configuration, participants often perceive a transparent red disk above a white cross. Nakayama et al. (1990) tested various modifications of this basic configuration, as well as of other illusions, where a transparent area is perceived. They conclude from their results that an illusion of transparency only occurs, if the objects are in the correct location, i. e., the transparent object is perceived to be in front of another object, and at the same time the luminance relationship is configured in a way that allows for an interpretation that the light is filtered by the transparent object (Nakayama et al., 1990). This means that the relationships between object positions is combined with other features of the objects to infer a sensation of

transparency, as well as object boundaries, which are not visible. Treisman (1996) cites these findings as an example of conditional binding, i. e., a binding, where relationships between properties have to be taken into account to make a meaningful interpretation.

Further, evidence for the necessity of inference processes in perception is indicated by the theory of event coding. According to Hommel et al. (2001) the event files do not contain proximal features to represent actions, but rather distal features corresponding to our action goals. There is a number of possibilities in which we can use one object to manipulate another object. In most cases these indirect manipulations will be learned and retrieved automatically. For example, it is unlikely that we reason about the effect of using a light switch every time we use it. Rather we rely on stored knowledge about the relationship between switches and lights. However, in other cases, for example when using a new tool for the first time, we do need to reason about the possible distal effects that we can produce with this tool. The same goes, if we use a tool differently than before, for instance, if we use a book to carry objects instead of reading it. In these cases, we have to reason about the effects our actions will have, for example to know that a book may achieve the distal effect of moving the objects, while a single sheet of paper may tear from the weight, and thus would not achieve our goal. This requires both (intuitive) knowledge about the physical world, as well as inference from this knowledge. The theory of event coding does not specify how distal an effect can be while still being included in an event file. If the results of decisions can be included in event files, further investigation is needed to test how many steps of inference can be done, or how long a given cause and effect chain can be, until the result cannot be bound anymore.

Furthermore, Glöckner et al. (2008) present a model of decision making that is based on a model that was developed for explanation of perceptual processes. Glöckner (2010) argues that models of perception in general may provide models for decision behavior. However, if models of perception provide a basis for decision making, this is strong evidence that research on decision making may prove useful for understanding perceptual

processes. This is especially the case in lines of research, where similar models are used. In the current case, both HiTEC (Haazebroek & Hommel, 2009a; Haazebroek et al., 2011, see also Section 2.3) as well as PCS are based on bidirectional neural networks with inhibitory connections between nodes representing the subjective experience, i. e., the feature codes in the case of HiTEC and the Options in case of PCS. In both networks activation at higher layers is spread back to lower layers, which accounts for instance for the Simon effect (J. R. Simon & Wolf, 1963) in case of HiTEC and for changes in subjective cue validities in case of PCS. While these networks are similar in some ways, there are also some differences. For example, PCS does not include any notion of common coding, while this is a basic design feature for HiTEC. Also there is no binding in PCS. And while HiTEC proposes a fixed network that is reused for multiple tasks, PCS requires the network to be constructed on the fly for each task at hand. The parallel indicated at the behavioral level investigated in this thesis, indicates that further models should try to combine these models more closely to arrive both at better models for perception and action control as well as better models for decision making.

Whether decision results are represented in separate decision files or together with other types of perception and action features in event files is unrelated to the question if these files play a role in automatization of decisions. Rather, if cues, decisions and perception/action-features are bound together in one single file, this can lead to more potential for automatization. In a combined event file, each cue and feature can be used to retrieve the rest of the event file.

9.2.2. Implications for Decision Making

Besides implications for the field of perception and action control, the current research also has implications for the field of decision making. Section 9.2.1 already hints at some implications this research may have, e. g., concerning automatization in decision making. However, there are several additional implications that follow from the presented results.

Recent research indicates that the presentation mode influences the decision (e. g., Armel, Beaumel, & Rangel, 2008; Bröder et al., 2013; Platzer & Bröder, 2012). While these studies directly manipulate the attention towards cues or the results of the decision, the nature of the decision problem which is presented to the participants is less well investigated. Treisman (1988) indicates that object files are used to track and update objects in episodic and short-term memory. This also means that different object files are created in decision problems depending on which objects are mentioned. For example, in a city size task, the two options are real-world objects. All cues, e. g., if one of these cities has an airport, are features of the city itself, and hence will be bound to this object. Also the final decision is done in terms of these objects, i. e., one of the objects is selected. In the case of a disease task, like in this thesis, there is only one object, the patient that has to be diagnosed. All symptoms are features of the patient, i. e., they have to be bound to the single object present. The decision itself is not done as a decision between different objects, but rather as a decision between possible features (diseases) of the patient. The feature integration theory indicates that the binding structure may be different, but so far there does not seem to be any research, which investigates how these different binding structures relate to the decision process. While the research presented here only indicates that binding structures have implications for decision making, it has only begun to investigate in which ways bindings may play a role. Still, the research presented here at least indicates that further research in this direction may prove fruitful.

Furthermore, bindings and binding research should be taken more into account in the interpretation of results in the field of decision making. For example, Bröder et al. (2013, Experiment 2) presented participants with a task where they had to decide who would win a fictitious card game. As cues the participants received the binary judgment of more or less reliable experts. In the routinization phase, an equal number of trials could be solved correctly both by repeatedly choosing the same player or by using the take the best heuristic based on the expert judgments. Then the routinization phase was either

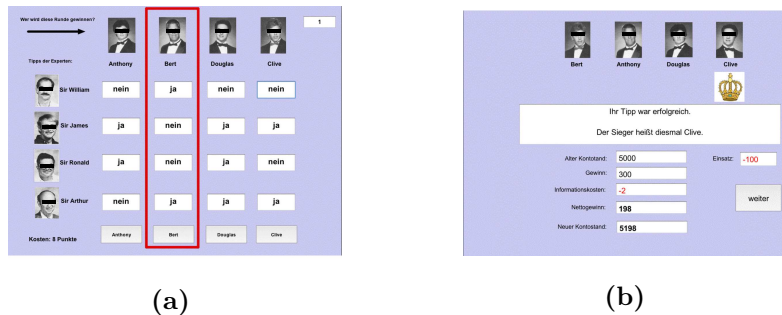


Fig. 9.2. Presentation of the feedback in Experiment 2 of Bröder, Glöckner, Betsch, Link, and Ettlin (2013, p. 207). In the cue feedback condition (a) the winning players and the cues are highlighted, while in the option feedback condition (b) only the winning player is indicated.

followed by trials (test phase) in which the same player was repeatedly the correct choice (option success condition, OS) or where the take the best strategy repeatedly indicated the correct choice (strategy success condition, SS). Furthermore, the way the result of the decision was presented was manipulated as an additional factor. In the option feedback condition the winning option was highlighted, while in the cue feedback both the winning option and the cues for that option were highlighted (see Figure 9.2). The variation in the feedback had an impact on the decision method that was used by the participants. In the option feedback group participants were more likely to select the same option repeatedly, than in the cue feedback condition. Also when the option success condition was paired with the cue feedback condition or vice versa, participants were considerably worse in determining the winner of the card game. Bröder et al. (2013) interpret this finding, by indicating that attention was modulated by the different presentation modes, thus reinforcing the option in the option feedback condition and reinforcing cue based strategies in the cue feedback condition. A different interpretation indicated by the research presented here, could be that different bindings are constructed depending on how the feedback is presented. In case of the option feedback (see Figure 9.2a), the players are directly linked to win or lose information, so that this information can be easily bound to the player itself. In the other condition not only is the winning player

indicated, but the player is also linked to the cues that are given (see Figure 9.2b). In this case a different event file may be constructed that consists of both the player as well as the cues. Furthermore, this interpretation is not in conflict with the interpretation presented by Bröder et al. (2013) that attention and reinforcement play a role for the difference in behavior. Rather the idea is that event files, including cues and decisions, are part of the underlying mechanism that modulates reinforcement. Given that the construction of bindings is modulated by attention (Treisman, 1988), this may also explain other findings in which a modulation of the attention has changed the decision behavior. Furthermore, Söllner, Bröder, and Hilbig (2013) presented the cue information either in a standard matrix format, in a unstructured matrix format, or as an unstructured “map”. Only in case of the structured matrix, the decision behavior could be matched to PCS, whereas in all unstructured cases, decision behavior better fitted heuristics. This finding is interpreted in the sense that the automatic processes used for constrained maximization require the information to be presented in a structured way. This finding is also in line with the idea that the same automatic pattern completion processes, which are part of the theory of event coding, also are the basis for decision making. At least the unstructured map should impair binding processes, as these processes rely on spatial proximity and structuring (Frings & Rothermund, 2011). In the case of the unstructured matrix this is less clear, and further investigation is needed about binding processes in this presentation format.

A different interpretation of the findings presented here could also be applied to recurrent decision making. Looking at the repetitions instead of the errors, this indicates that participants were in general more likely to repeat a previous decision in cases of ICR trials than in ICC trials³. This may indicate a simple heuristic, which was used: “If the environment changes, change the decision, and if the environment is the same,

³In ICR-DC and ICC-DC trials, an error meant a repetition, since the previous decision should have been repeated, whereas in ICR-DR and ICC-DR trials a correct choice was a repetition.

repeat the decision.” This heuristic could aim at a solution to the exploration/exploitation conflict (March, 1991, see Section 4.1.2), i. e., an individual using this heuristic would constantly monitor the environment and exploit as much as possible as long as the environment remains stable. As soon as a change is detected, it switches back to exploration, to try to get a better solution. The environment could serve as a cue here that indicates a sudden change in the payoff structure, so that a new exploration may be fruitful. However, in the light of the results of Experiment 3a, this heuristic is too simplistic. If the complete environment is monitored, a change in the weekday should also have triggered new exploration behavior, resulting in higher error rates in DR trials. As this was not the case, it is likely that information only leads to new exploration behavior, if it is somehow related to the problem. This interpretation views the effects at the level of ecological rationality (Todd & Gigerenzer, 2012), i. e., why this behavior helps in making good decisions. At the same time, this interpretation does not conflict with the theoretical account of underlying event file mechanisms and common coding in decision making. Rather these two interpretations are complementary, the heuristic could explain why this behavior exists ecologically, whereas the theory of event coding may explain how it is implemented.

9.3. Limitations

When interpreting the results of this thesis some limitations of the experiments should be considered.

In the first series of experiments (Experiment 1a to Experiment 1c) all factors (irrelevant cue relation, relevant cue relation, disease relation, and decision relations) could not be varied orthogonally. Hence, there was a confound between relevant cue relation with decision relation in Experiment 1a and between relevant cue relation and disease relation with decision relation in the other two experiments. That distractor-response binding is not only an artifact due to the confound was shown by Frings et al. (2007, see also

Frings, & Moeller, 2010; Giesen, & Rothermund, 2011). Nevertheless, there most likely was a binding between relevant cue and decision as well in these experiments, which also influenced RTs (e.g., Henson et al., 2014). In order to test this possible influence in Experiment 1a the analysis was done for all trials, as well as only for trials, where the relevant cue changed. In this analysis, the crucial interaction was only present descriptively. Still, the experiments in Chapter 7 and 8 eliminated the constraint, and could show that irrelevant cues are bound to decisions. Furthermore, the most basic hypothesis, i.e., that binding effects in general play a role for decision making, is supported by the finding of the first experiments regardless of whether the effects are caused by distractor-response binding or target-response binding mechanisms.

The experiments presented here, show that decisions are influenced by irrelevant information on a trial to trial basis in a similar way as in classification tasks. However, Experiment 1c, 3c and 3d do not indicate clearly that this influence is caused by processes like distractor-response binding in action control. Experiment 1c indicates that the bypass rule (Krueger & Shapiro, 1981) may also provide a valid explanation. However, the lack of the interaction between irrelevant cue relation and decision relation may also have been due to insufficient test power. Also, the delay between prime and probe may have been too long to ensure that the event file is kept active over the whole prime-probe sequence, including fillers. Another replication, with a larger sample size and a better control of the delay between prime and probe should be undertaken to clarify whether the effect is due to binding effects or to the bypass rule. It should be noted, however, that the bypass rule was developed based on experiments using only trial $N - 1$ to N interactions (Fletcher & Rabbitt, 1978; Krueger & Shapiro, 1981; Smith, 1968), so that the crucial assumption, i.e., that interactions between trials other than $N - 1$ to N do not exist, was not tested. Also, the bypass rule is a behavioral rule, whereas SR binding is a proposed cognitive mechanism. It could well be the case, that stimulus and distractor-response binding are the mechanisms which causes the behavior according to the bypass rule. Smith (1968, p.

435) actually points out that the observed behavior is caused by a “S-R bond or memory trace, which remained activated”.

In the analysis of Experiments 3a and 3b, data from these experiments and Experiment 2a was compared. Since these experiments were done at different times, the effects found for this comparison may also be explained by cohort or season effects. In general, between-experiment results should not be interpreted causally (e. g., Bröder et al., 2013). Hence, the results from these comparisons should only be seen as a hint for the proposed influence of semantic relation and time pressure. To gather more reliable data, these experiments should be repeated with the between-subject factors as within-subject factors.

In Experiment 3c it could not be clearly shown that irrelevant cues are bound to decisions. Instead this experiment also allowed for an alternative interpretation, i. e., that irrelevant cues are bound to response codes in decision tasks in the same way as in classification tasks. However, a further explanation could be that irrelevant cues are bound to decisions as well as response codes (Horner & Henson, 2009), but one of the bindings is stronger and hence overruled the effect of the other. Future experiments should try to further dissociate bindings of response codes and decisions, in order to investigate what exactly is bound in decision tasks (for a overview of the nature of the response component see Giesen, 2014, section 1.4).

In Experiment 3d no interaction could be found in the confidence ratings, although a distractor-response binding effect was found for the number of incorrect decisions. However, an analysis of the confidence also did not show a significant effect of the cue validity, although in decisions with a cue with $v = .80$ one would expect people to be more confident than in decisions with $v = .60$. The lack of a significant effect of cue validity clearly shows that the operationalisation of the confidence rating did not work as expected. This effect cannot be attributed to an overconfidence bias (Lichtenstein, Phillips, & Fischhoff, 1977), since an overconfidence bias would cause participants to

report higher confidence in both types of trials, but keep the difference between these trials.

In general, it is also unclear if distractor-response binding influences decisions for other paradigms than the one used in this thesis. In this thesis I analyzed decisions between two features of the same object, however, the more common case are decisions between two objects with the cues presented in form of a matrix (e. g., Söllner et al., 2013). It is unclear, how binding processes generalize to this type of decision tasks, especially since the number of objects that may have to be represented by the cognitive system is different. Moreover, it is also unclear how this effect generalizes to decisions in day-to-day situations.

10. Conclusion and Outlook

10.1. Conclusion

In this thesis I presented evidence that distractor-response binding also plays a role in decision making under certainty as well as under uncertainty. Therefore, the theory of event coding should be considered more in the field of decision making. Although the theory of event coding has been envisioned as a theory of perception and action control, recent theories of decision making have indicated that decision making may be based on mechanisms that originally evolved for perception (Glöckner & Betsch, 2008). Also, inference processes have been frequently seen as a necessary part of perception and action control (Nakayama et al., 1990; Rock, 1983; Treisman, 1996). Yet, there is only little research on the implications of research on decision making on research of perception and action control and vice versa. The results presented in this thesis, further indicate that mutual cooperation between these two fields may lead to further advances in both areas. This thesis is one of the first steps for uncovering common processes in action control and decision making. While possible implications have been envisioned on a theoretical basis, no empirical tests have been performed yet. Further research is clearly needed to see how these two fields can profit from each other.

10.2. Outlook

The work presented here presents one starting point for a deeper cooperation between researchers in the field of action control and decision making. Another possible link has been created by the use of perceptual models in decision making (Glöckner & Betsch, 2008). Future research should indicate how these two links between the two fields can be combined. For example, PCS is a model that is targeted at explaining one-shot decision making. How could this model be modified, so that it can also include binding mechanisms? On the other hand, HiTEC as a computational model for perception and action control. How well would this model do when presented with decision tasks? Can HiTEC account for the effects which are known in decision making? Also both models show a great deal of structural similarities, but also structural differences. Is it possible to combine these models, creating a model, which can both perform decision making, as well as perception and action control? If the theory of a common basis for perception and decision making should gather more support, these future modeling efforts can provide greater insight about the mechanisms underlying the common basis.

However, this thesis not only indicates the need for further modeling efforts, but also for further experimental evaluation. In Section 9.2.1 I posed the question, whether bindings for decisions are stored in the same structure as bindings for action control, or whether both effects are based on separate structures. Further experiments should address this question. For example, if both bindings are stored in the same structure, it should be possible to design an experiment in which a decision prime influences a classification probe and vice versa.

Also, the combination with research on decision making introduces a new direction in binding research. Distractor-response binding produces both facilitation as well as impairment effects, which on a global perspective cancel each other out. However, these effects only cancel each other out in balanced laboratory experiments. From a perspective of decision making, one may assume that these mechanisms are ecologically rational (Todd

& Gigerenzer, 2012). In that for case day-to-day situations in which binding mechanisms are used, a statistical bias towards situations which induce facilitation should be found. For example, in that case one should find more situations where the decision needs to be repeated in case a possible distractor or environmental factor is repeated, than situations for which the decision has to be changed. This would lead to more situations where one can benefit from binding than situations where the behavior is impaired. Another possible idea about the ecological rationality I presented here, was that these mechanisms are used to solve exploration/exploitation conflicts. In that case, it should be possible to design experiments in which routine behavior is overruled by changes in irrelevant cues.

Moreover, while the link between routines and binding mechanisms can be seen on a theoretical basis, the empirical evidence is much less clear. For example, it could be tested, if distractor-response binding effects become stronger, if the prime is repeated multiple times, indicating a further link between routines and binding mechanisms. Also, in experiments on routines, feedback is usually presented (e. g., Betsch et al., 2004), while binding processes also take place without feedback. What role does feedback play here? Are binding effects increased by additional feedback, or is the underlying mechanism unaffected by feedback? Can routines be established without feedback, or is feedback required for the establishment of routines?

All these questions posed above, show that this thesis can only mark the beginning of a new direction of research, which may give further insights in both decision making processes as well as into action and perception.

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Eidesstattliche Erklärung

Hiermit erkläre ich an Eides statt, dass ich die vorgelegte Dissertation selbst angefertigt und alle von mir benutzten Quellen und Hilfsmittel in der Arbeit angegeben habe.

Trier, den 27. November 2014

Nadine Nett